Coherent Receiver Arrays for Astronomy and Remote Sensing

REPORT OF A STUDY PROGRAM

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Preface

The subject of the KISS Study Program on Coherent Receiver Arrays for Astronomy and Remote Sensing was large arrays of coherent detectors for the frequency range from tens to hundreds of gigahertz: their scientific applications, technical readiness, and future development. The study had the following objectives:

1. Explore the science that would be enabled by large arrays for cosmology, astrophysics, planetary science, atmospheric science, and remote sensing of the Earth. Would this be "transformational" science?

2. Explore the technical promise and projected capabilities of arrays over the next decade. What are the current limitations to their development? (funding?, shortage of groups working on this worldwide?, other?)

3. Determine the key technical developments that are needed both for arrays themselves and for digital backends. Identify prototypes that should be the subject of follow-on funding.

4. Devise a roadmap for detector array and array spectrograph development over the next decade, including the prototypes, the likely sources of funding, the principal instrumental groups and industries that should be involved, etc.

5. Recommend specific prototype development programs that should be funded over the next 2–3 years to ensure timely exploitation of this rapidly developing capability.

The study program was led by Anthony C. S. Readhead (Barbara and Stanley R. Rawn, Jr., Professor of Astronomy at the California Institute of Technology) and Charles R. Lawrence (Principal Scientist, Astrophysics Element, Jet Propulsion Laboratory). This report was compiled from presentations and contributions from participants at two workshops, held at the California Institute of Technology on July 21–25, 2008 [1], and March 22–24, 2009 [2]. The report was edited by Readhead, Lawrence, and Timothy J. Pearson.

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Summary

Monolithic Millimeter-wave Integrated Circuits (MMICs) provide a level of integration that makes possible the construction of large focal plane arrays of radio-frequency detectors—effectively the first "Radio Cameras"—and these will revolutionize radio-frequency observations with single dishes, interferometers, spectrometers, and spacecraft over the next two decades. The key technological advances have been made at the Jet Propulsion Laboratory (JPL) in collaboration with the Northrop Grumman Corporation (NGC). Although dramatic progress has been made in the last decade in several important areas, including (i) packaging that enables large coherent detector arrays, (ii) extending the performance of amplifiers to much higher frequencies, and (iii) reducing room-temperature noise at high frequencies, funding to develop MMIC performance at cryo-temperatures and at frequencies below 150 GHz has dropped nearly to zero over the last five years. This has severely hampered the advance of the field. Moreover, because of the high visibility of < 150 GHz cryogenic detectors in astrophysics and cosmology, lack of progress in this area has probably had a disproportionate impact on perceptions of the potential of coherent detectors in general.

One of the prime objectives of the Keck Institute for Space Studies (KISS) is to select crucial areas of technological development in their embryonic stages, when relatively modest funding can have a highly significant impact by catalyzing collaborations between key institutions world-wide, supporting in-depth studies of the current state and potential of emerging technologies, and prototyping development of key components—all potentially leading to strong agency follow-on funding.

The KISS large program "Coherent Instrumentation for Cosmic Microwave Background Observations" was initiated in order to investigate the scientific potential and technical feasibility of these "Radio Cameras." This opens up the possibility of bringing support to this embryonic area of detector development at a critical phase during which KISS can catalyze and launch a coherent, coordinated, worldwide effort on the development of MMIC Arrays. A number of key questions, regarding (i) the importance and breadth of the scientific drivers, (ii) realistic limits on sensitivity, (iii) the potential of miniaturization into receiver "modules," and (iv) digital signal processing, needed to be studied carefully before embarking on a major MMIC Array development effort led by Caltech/JPL/NGC and supported by KISS, in the hope of attracting adequate subsequent government funding. For this purpose a large study was undertaken under the sponsorship and aegis of KISS. The study began with a workshop in Pasadena on "MMIC Array Receivers and Spectrographs" (July 21–25, 2008)[1], immediately after an international conference "CMB Component Separation and the Physics of Foregrounds" (July 14–18, 2008)[2] that was organized in conjunction with the MMIC workshop. There was then an eight-month study period, culminating in a final "MMIC 2 Workshop" (March 23–27, 2009).[3] These workshops were very well attended, and brought

[1]http://kiss.caltech.edu/workshops/mmic/mmic.html
[2]http://planck.ipac.caltech.edu/content/ForegroundsConference/Home.html
[3]http://kiss.caltech.edu/workshops/mmic/mmic2.html

together the major international groups and scientists in the field of coherent radio-frequency detector arrays. A notable aspect of the workshops is that they were well attended by young scientists—there are many graduate students and post-doctoral fellows coming into this area. The two workshops focused both on detailed discussions of key areas of interest and on the writing of this report. They were conducted in a spirit of full and impartial scrutiny of the pros and cons of MMICs, in order to make an objective assessment of their potential. It serves no useful purpose to pursue lines of technology development based on unrealistic and over-optimistic projections. This is crucially important for KISS, Caltech, and JPL which can only have real impact if they deliver on the promise of the technologies they develop. A broad range of opinions was evident at the start of the first workshop, but in the end a strong consensus was achieved on the most important questions that had emerged. This report reflects the workshop deliberations and that consensus.

The key scientific drivers for the development of the MMIC technology are: (i) large angular-scale B-mode polarization observations of the cosmic microwave background—here MMICs are one of two key technologies under development at JPL, both of which are primary detectors on the recently-launched *Planck* mission; (ii) large-field spectroscopic surveys of the Galaxy and nearby galaxies at high spectral resolution, and of galaxy clusters at low resolution; (iii) wide-field imaging via deployment as focal plane arrays on interferometers; (iv) remote sensing of the atmosphere and Earth; and (v) wide-field imaging in planetary missions. These science drivers are discussed in the report.

The most important single outcome of the workshops, and a *sine qua non* of this whole program, is that consensus was reached that it should be possible to reduce the noise of individual HEMTs or MMICs operating at cryogenic temperatures to less than three times the quantum limit at frequencies up to 150 GHz, by working closely with a foundry (in this case NGC) and providing rapid feedback on the performance of the devices they are fabricating, thus enabling tests of the effects of small changes in the design of these transistors. This kind of partnership has been very successful in the past, but can now be focused more intensively on cryogenic performance by carrying out tests of MMIC wafers, including tests on a cryogenic probe station. It was felt that a properly outfitted university laboratory dedicated to this testing and optimization would be an important element in this program, which would include MMIC designs, wafer runs, and a wide variety of tests of MMIC performance at cryogenic temperatures.

This Study identified eight primary areas of technology development, including the one singled out above, which must be actively pursued in order to exploit the full potential of MMIC Arrays in a timely fashion:

1. Reduce the noise levels of individual transistors and MMICs to three times the quantum limit or lower at cryogenic temperatures at frequencies up to 150 GHz.

2. Integrate high-performing MMICs into the building blocks of large arrays without loss of performance. Currently factors of two in both noise and bandwidth are lost at this step.

3. Develop high performance, low mass, inexpensive feed arrays.

4. Develop robust interconnects and wiring that allow easy fabrication and integration of large arrays.

5. Develop mass production techniques suitable for arrays of differing sizes.

6. Reduce mass and power. (Requirements will differ widely with application. In the realm of planetary instruments, this is often the most important single requirement.)

7. Develop planar orthomode transducers with low crosstalk and broad bandwidth.

8. Develop high power and high efficiency MMIC amplifiers for LO chains, etc.

Another important outcome of the two workshops was that a number of new collaborations were forged between leading groups worldwide with the object of focusing on the development of MMIC arrays.

2

Introduction

Over the last five decades Caltech/JPL has played a significant role in the development of high sensitivity electromagnetic detectors and receivers for astrophysics, cosmology, remote sensing, and telecommunications. These include, for example, key roles in developing parametric amplifiers and maser receivers for the Deep Space Network and astronomical applications, SIS-mixers, High Electron Mobility Transistors (HEMTs), Monolithic Millimeter-wave Integrated Circuit amplifiers (MMICs), spiderweb bolometers, Transition Edge Sensors (TESs), Polarization Sensitive Bolometers (PSBs), Microwave Kinetic Induction Detectors (MKIDs), and antenna-coupled superconducting bolometers. Leading such developments over the years, Caltech/JPL has managed to position itself to play a major role in many space missions. A prime example is the recently-launched *Planck* Mission, which uses two types of detectors—bolometers and MMICs—both of which were developed and constructed for this mission at JPL.

At present Caltech/JPL is actively pursuing several major initiatives in the area of astronomical detector development. This report addresses one of these initiatives—the development of MMIC Arrays for cosmological, astrophysical, and remote sensing applications. The primary science driver for this initiative is its potential for observations of the large angular scale ($\gtrsim 1^\circ$) B-mode polarization signal of the cosmic microwave background radiation (CMB). Other fundamental science drivers are spectroscopic, large field-of-view imaging for astrophysics, and for remote sensing of the atmosphere, of the Earth, and of planets. JPL has developed a unique relationship with the Northrop Grumman Corporation (NGC, formerly Northrop Grumman Space Technology, or NGST, and before that TRW), which has yielded by far the most sensitive MMICs for astrophysical observations. However, although several important areas have been well supported recently (primarily by DoE), including (i) packaging of large coherent detector arrays, (ii) extending the performance of amplifiers to much higher frequencies, and (iii) reducing noise at room temperature at high frequencies, agency funding of cryogenic development of amplifiers for scientific instruments has been poor, notwithstanding the fact that the JPL group leading this effort is the undoubted world leader in producing both individual MMIC amplifiers and MMIC Arrays, and that many believe that these arrays will lead to a revolution in radio astronomy, both on the ground and in space, over the next two decades.

The subject of the KISS Study Program on Coherent Receiver Arrays for Astronomy and Remote Sensing was large arrays of coherent detectors for the frequency range from tens to hundreds of gigahertz: their scientific applications, technical readiness, and future development.

If one has n detectors, each with noise temperature T, that can observe a given area of sky, the effective noise of the signals from the n detectors combined is $Tn^{-1/2}$. The effective noise drops linearly with the noise of the individual detectors, but only as the square root of the number of detectors. As a result, historically, it has been more cost-effective to reduce T than to increase n. This has certainly been the case with amplifiers. Until recently, the noise temperature T of amplifiers has been quite a long way from fundamental limits, and large n has been prohibitively expensive. It made sense to concentrate on reducing the noise of individual detectors before making arrays. However, over the last decade the situation has changed. Breakthroughs have been made in both noise performance and packaging. Instruments with both low T and large n are within reach at an affordable cost. This is the opportunity for a second revolution in radio astronomy, and the motivation for the KISS Study Program.

Currently MMIC amplifiers are operating at $\sim$ 7 times the quantum limit at frequencies up to $\sim$ 150 GHz, and we believe that it should be possible to improve their performance by at least a factor of two. Note that a factor of two improvement in total system noise reduces by a factor of four the number of detectors needed to achieve a given sensitivity level. Moreover, recent breakthroughs in packaging enable large n at modest cost. The time is ripe, therefore, both to improve the noise of individual amplifiers and to develop large arrays.

2.1 Scientific opportunities

Coherent receiver arrays will enable new types of observations of unprecedented scope and sensitivity. The areas of fundamental research that will be addressed include:

1. **The Cosmic Microwave Background (CMB).** Over the last decade the field of cosmology has been transformed by observations of the CMB, enabled by advances in two detector technologies: bolometers and high electron mobility transistors (HEMTs). The extraordinary CMB results complement other cosmological observations and show convincingly that the universe is dominated by dark matter (85% of the matter content of the universe) and dark energy (75% of the energy content of the universe), and that the geometry of the universe is Euclidean, to within 2%. The CMB field is now focussing on detecting the large-angular-scale B-mode polarization, which would demonstrate that the Universe passed through an early inflationary stage and would reveal the energy scale of inflation; and on measuring secondary anisotropies, particularly the Sunyaev–Zel'dovich (SZ) effect, which promise further transformational discoveries.

2. **Millimeter-wave spectroscopy.** Various chemical tracers have emission lines in the millimeter wave-band and these offer a wealth of information. They can be used to determine gas properties of the interstellar medium (ISM) such as the mass, kinematics, physical conditions, and chemical composition as well as the magnetic field densities in our own and nearby galaxies. These observations will allow understanding of key problems in astrophysics such as star formation, the life cycle of the ISM, and the chemical evolution of galaxies. In order to understand the dynamics and chemistry of the interstellar medium and also star formation in both our own galaxy and other nearby galaxies, we need to map very large fields of view at high spectral resolution. This requires focal plane arrays on large telescopes such as the Green Bank Telescope (GBT), or on interferometers such as CARMA or ALMA.

3. **Earth remote sensing.** Advances in Earth remote sensing and weather forecasting have been driven by measurement of the natural radio emission from the Earth's surface, the oceans, and the atmosphere. Rainfall, wind, cloud coverage, sea-surface temperatures, soil moisture, snowpack depth, and sea-ice extent can all be monitored through satellite-based radio observations. These data will be essential for monitoring and understanding global warming. Note that since these are time-varying phenomena one requires both high spatial resolution and high time resolution, and hence high sensitivity.

4. **Planetary science.** Millimeter and submillimeter observations from interplanetary spacecraft offer a unique opportunity to detect and identify polar molecules through a variety of active, passive, and lander-based *in situ* instruments. The key science goals of these experiments will be to determine gas phase chemical compositions and isotope ratios and to search for organic species.

2.2 Technical opportunities

A major advance in the last decade is the development of Monolithic Microwave Integrated Circuits (MMICs), which combine multiple microwave devices (including low-noise HEMT amplifiers and mixers), that were formerly constructed from discrete components, into small integrated circuits. It is the small size of these devices and their ability to be mass-produced that enables large arrays of receivers to be constructed. Commercial applications such as cellular phones have driven the development of MMICs, but for scientific applications additional development is needed. JPL is the world leader in this work.

Two critical areas where further development is needed are: (i) To determine the best approaches for producing low-noise amplifiers that are significantly more sensitive than those available today, and to see how closely we can approach the fundamental quantum limit on the sensitivity of coherent devices; (ii) To explore methods of modularization, packaging, and automated assembly of the devices to make them suitable for focal plane array applications.

There are three relevant areas of rapid technical innovation that make this program particularly timely:

MMIC device development: Northrop Grumman Corporation (NGC), in close collaboration with JPL, has been leading the field in pushing the limits on MMIC performance for the last decade. There have been many improvements leading to lower noise levels and higher-frequency operation. The most recent of these is the development of HEMTs with 35 nm gate lengths. The relevant developments are discussed in detail in Chapter 6.1.

Module development: JPL has led the field in the development of MMIC modules for scientific applications. The modules are designed for mass production, close packing, and excellent performance. For example, arrays of tens to hundreds of JPL-designed modules are already being used in one of the most sensitive experiments for studying the B-mode polarization of the CMB: QUIET (the "QU Imaging ExperimenT").

Digital processing developments: With continued rapid improvement, the performance of analog-to-digital converters and multipliers has crossed a threshold. It is now possible to contemplate powerful digital processors and correlators that meet the low-power requirements of space projects, enabling us to develop instruments that were inconceivable or prohibitively expensive only a few years ago. The basic technological progress is driven by commercial demands; however, implementation issues must be addressed.

2.3 Scope of the study

The investigation of the potential and limitations of the HEMT/MMIC technology is a challenge tailor-made for the Keck Institute for Space Studies. Caltech and JPL are already playing a unique and critical leading role in both the science (including studies of the CMB, high-resolution spectroscopy, and remote sensing), and the technology (coherent detectors operating near the quantum limit, improved incoherent detectors, arrays of thousands of detectors—effectively the first radio cameras—and interferometers of unprecedented power and complexity).

Instruments with both low noise temperatures and large numbers of pixels are now within reach at an affordable cost. It is now possible to put interferometers with large numbers of pixels in space with digital correlators that can cross-correlate a million baselines. Our goal in this report is to lay out a roadmap for this activity.

2.4 This report

This report begins with an overview of coherent detectors and technology (Chapter 3) to introduce their power and applications. Chapter 4 presents some of the breakthrough science in cosmology, astrophysics, Earth science, and planetary science that will be enabled by large arrays of coherent receivers, and describes some conceptual designs for possible instruments. These conceptual designs highlight some of the improvements in technology that are needed to bring receiver arrays to full maturity. These requirements are summarized in Chapter 5. Chapter 6 reviews the current state of the technology and future directions. Finally, Chapter 7 lays out a prioritized roadmap for the developments that must be achieved to realize the full promise of coherent receiver arrays.

3

Overview of Coherent Detectors and Arrays

3.1 Definitions and general description

Coherent detectors such as amplifiers preserve the phase of the incoming electromagnetic signal as well as its amplitude. They are active devices with gain. Multiple copies of the incident signal can be produced and used without significant further reduction in signal-to-noise ratio. Two important applications of this feature of coherent detectors are (i) the multiplying interferometer, which revolutionized radio astronomy more than 50 years ago and made instruments such as the VLA, the VLBA, CARMA, and ALMA possible, and (ii) the high-resolution heterodyne spectrograph. The multiple signal copies may be used in ways that allow significant control of systematic errors arising in the signal path: in an N-element interferometer, for example, there are $N-1$ signals associated with each antenna, feed, and detector element, and these can be used, along with phase switches, to isolate and eradicate many sources of systematic error.

There is a cost associated with the phase-preservation of these detectors, which takes the form of an additional source of noise produced by quantum fluctuations. In terms of system noise equivalent temperature, this *quantum noise* (often called the *quantum limit*) can be written as $q = h\nu/k \approx [\nu/20\,\mathrm{GHz}]\,\mathrm{K}$.

Direct or "incoherent" detectors such as bolometers measure only the amplitude of the signal, not its phase. They do not pay this "*quantum tax*," but neither can they provide multiple copies of the input signal. Amplifiers and bolometers also differ in their susceptibility to various sources of systematic error. In the pursuit of extremely weak signals, such as those that we are searching for in polarized CMB radiation, having two different technological approaches, with different systematic errors, is potentially invaluable. A full evaluation of the relative merits of MMICs and bolometers is complex and should be made in the context of complete systems. We therefore do not attempt such a comprehensive review here. Instead, we focus on the current strengths and weaknesses of MMIC technology, bringing in bolometers when comparisons are informative and fruitful.

Detector systems based on amplifiers have some significant practical benefits, including: large dynamic range; operation over a broad temperature range, with sensitivity improving typically by a factor of ten between room temperature and 20 K; insensitivity to cosmic rays and microphonics; and simple filtering taking advantage of the inherent bandpass of amplifiers.

3.1.1 The power of multi-pixel arrays

For technical reasons, radio receivers for astronomy and remote sensing have been limited to a small number of detectors—often only one—allowing very few pixels to be imaged simultaneously. Sparse interferometers are an exception, but even there fields of view are relatively small, so that mapping a large area takes a very long time. Recent technological advances in the miniaturization of detectors and in digital signal processing have now made arrays of hundreds or thousands detectors practicable. Multi-pixel arrays will permit major advances in imaging sensitivity, speed, and fidelity:

- The sensitivity of individual detector chains, including all active and passive components, is approaching fundamental limits for both bolometers and amplifiers. Typical CMB instruments are already integrating on the sky for many months in order to detect signals at the microkelvin level. For observations of even fainter signals, such as the extremely faint B-mode polarization in the CMB, we need to reduce the noise by an additional factor of 10–100. The only way to achieve this in a reasonable integration time is through the use of large detector arrays.
- In astrophysics and remote sensing applications the speed of imaging a given area of sky, or of the Earth, is directly proportional to the number of detectors. Typical ground-based radio telescopes have costs in the range $3M–$100M, and most are heavily over-subscribed. An increase of a factor 10–1000 in observing efficiency will revolutionize observational radio astronomy and open up the field of wide-field imaging. Moreover, in observing the Earth, the better the angular resolution, the greater the sampling rate required.

Other fields of astronomy went through this revolution some time ago. For example, near infrared astronomy has graduated from single-pixel technology to arrays consisting of millions of detectors, and tens of thousands in space. In Figure 3.1 we show a 2-micron image of the Galactic Center made with a 65 000 pixel array in 2006, compared with a 1-pixel scan across this region in 1967.

Large detector arrays allow qualitatively different kinds of work than one or a few detectors. There is a good reason why a large array is not necessarily the first step. Suppose one has n detectors, each with noise T, that can observe a given area of sky. The effective noise if the signals from the n detectors are combined is $T/\sqrt{n}$. The effective noise drops linearly with the noise of the individual detectors, but only as the square root of the number of detectors. It is better to have fewer good detectors than more bad ones.

Until recently, the noise temperature T of amplifiers has been quite a long way from fundamental limits, and large n has been prohibitively expensive. It made sense to concentrate on reducing the noise of individual detectors before making arrays. However, over the last decade the situation has changed. Breakthroughs have been made in both noise performance and packaging. Instruments with both low T and large n are within reach at an affordable cost. This is the opportunity for a second revolution in radio astronomy, and the motivation for this KISS Study Program.

3.2 Three key applications of coherent arrays

Breakthrough science can be expected from three types of coherent arrays. These are:

- *Continuum systems*—arrays of detectors that integrate over a given frequency range ("bandpass") of the electromagnetic spectrum. If the components are arranged to be sensitive to polarization, such systems are called *polarimeters*;
- *Spectroscopic systems*—arrays of detectors that measure radiation as a function of frequency; and
- *Interferometers*—arrays of detectors that may be close-packed or sparse, depending on the combination of surface-brightness sensitivity and angular resolution desired, the signals from which are multiplied in pairs interferometrically.

It is easy to see how coherent arrays could be important in astrophysics up to at least 5 THz. At higher frequencies, quantum noise will dominate for any conceivable application. For the KISS Study Program, we will focus primarily on 15–300 GHz. Going to higher frequencies would require a program of larger scope than is possible here.

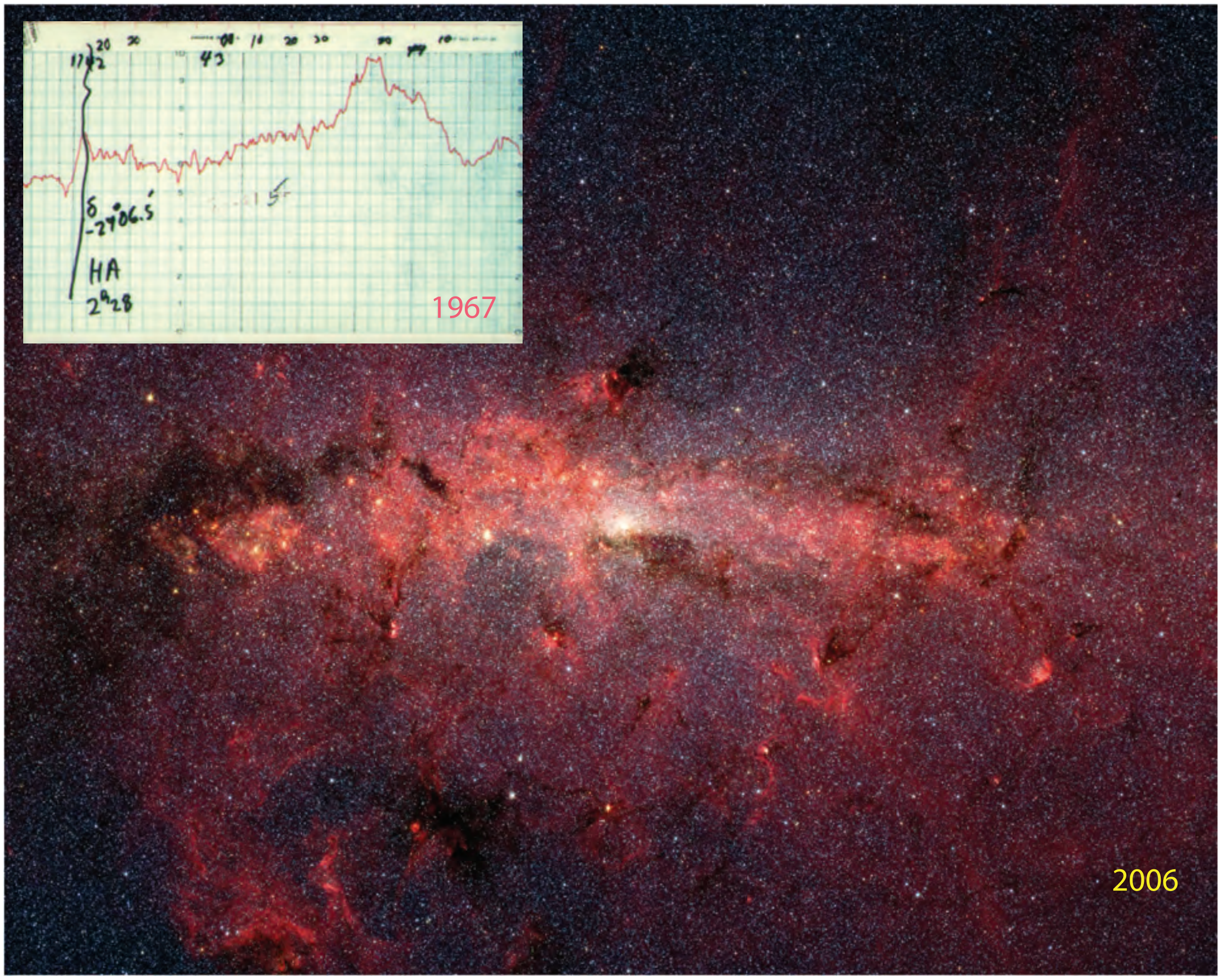

Figure 3.1: First infrared detection of the Galactic Center in 1967 (Neugebauer et al.), using a single detector scanned across the sky, compared to a 2006 image of the entire Galactic Center region (2MASS), using detector arrays with 65 000 pixels.

3.2.1 Continuum systems

The survey speed of a telescope measuring continuum radiation is directly proportional to the number of detectors that can be deployed in the focal plane of the telescope; the number is limited by the optics of the telescope and by packaging and signal-handling constraints. Broad-band sensitivity is usually an advantage. Both amplifier arrays and bolometer arrays have been deployed for continuum studies, most notably in studies of the CMB for which high sensitivity is essential and where the signal itself is broad-band. For polarization studies, two orthogonal polarizations must be measured in each detector element and combined to estimate the four independent Stokes parameters I, Q, U, and V. When coherent amplifiers are used, allowing the signals in each orthogonal polarization to be divided without noise penalty, all four Stokes parameters can be measured with just two amplifiers from the complex correlations $\langle LL^* \rangle$, $\langle RR^* \rangle$, $\langle RR^* \rangle$, $\langle LR^* \rangle$, and $\langle RL^* \rangle$. With bolometers, it is only possible to measure one Stokes parameter (or parameter combination) per detector.

3.2.2 Spectroscopy

Spectrometers can be characterized by their overall band-pass and their frequency resolution $R \equiv \nu/\Delta\nu$. Galactic spectroscopy of molecular lines requires high resolution ($cR \sim 1\,\mathrm{km\,s^{-1}}$ or better; $R > 300\,000$) to resolve the typically very narrow spectral lines in cold molecular clouds. Spectroscopy of high redshift galaxies requires far lower resolution ($\sim$ 100–200 $\mathrm{km\,s^{-1}}$), where the goal is to detect several spectral lines with maximum sensitivity in a wide bandwidth. Spectroscopy of nearby galaxies requires intermediate spectral resolution of $\sim 20\,\mathrm{km\,s^{-1}}$. The high resolution requirement for Galactic astrophysics immediately requires the use of coherent techniques. Since the size of spectrally multiplexing incoherent spectrometers scales with resolution, their physical size becomes prohibitively large for spectral resolutions of $R \sim 100\,000$ or greater. At low spectral resolution ($< 10\,000$) incoherent spectrometers have a distinct noise advantage in sensitivity and instantaneous bandwidth when compared with coherent techniques. For intermediate spectral resolutions, either approach can yield excellent performance, depending on the details of experiment implementation.

High-resolution coherent spectrometers can be implemented with MMIC amplifiers or SIS mixers. SIS mixers already offer very high sensitivity ($\sim$ 2 times the quantum limit) and wide tuning bandwidth, but, for a variety of reasons, in their implementation the instantaneous bandwidths are $< 10\%$, and, due to recent improvements in the sensitivity of MMICs and also due to the relative ease of implementation of broad bandwidths, MMICs are now replacing SIS mixers in the field. For example CARMA has decided to replace its current 3 mm SIS mixers with MMICs. MMIC amplifiers can be very broad band, and at 3 mm they can operate at $7\times$ the quantum limit at 20 K. As mentioned above, it is hoped to improve the sensitivity by developing a new generation of MMICs operating at $\leq 3\times$ the quantum limit in this wavelength range.

3.2.3 Interferometry

A key development of radio astronomy in the 20th century was the phase-switching, or multiplying, interferometer (Ryle, 1952). This approach dramatically reduced systematic errors that had plagued earlier adding interferometers and led directly to aperture synthesis interferometry. In the presence of ground spillover, and many other forms of large systematic error, all techniques of astronomical observation must provide a means of subtracting out these large signals. The essential feature of the multiplying interferometer is that any variations along the two signal paths apply only to the *difference* between the two signals arriving at the amplifiers. In many other instruments variations along the two signals paths apply to the *whole* signal, which is then later differenced. While it is true that in interferometry one is differencing signals to obtain an image, the fact that these are differences of small numbers results in a dramatic reduction in the systematic errors, and provides for routine operation at the thermal noise level (for months on end if need be), as is achieved by instruments such as the Westerbork array, the VLA, and the VLBA.

There are costs in complexity that must be paid for interferometry, the most critical of which are (i) the need for a stable correlator with the computing capacity to handle $N(N-1)/2$ complex combinations of the signals from the N antennas, and (ii) the need for delay lines and phase rotators to maintain coherence of the signals from different antennas at all times and across the entire receiving bandwidth. Over the last five decades methods have been developed that have overcome all of the key problems associated with the complexities and challenges of multiplying interferometry. One of the most important of these developments has been the use in the correlator of Walsh functions to remove "false fringes" due to various forms of "cross talk" that can arise in any multi-detector system.

A useful feature of interferometric arrays of detectors is that they may be close-packed or sparsely-packed, and thus they can be adapted in an optimal way to the combination of sensitivity and angular resolution that is desired.

When properly designed and implemented, interferometers have excellent rejection of a wide range of systematic errors, and this is particularly useful for high dynamic-range imaging and CMB studies:

- The interferometer point spread function (also known as the synthesized beam) depends on the array geometry and is usually more stable and can be measured more accurately than the PSF of a large mechanically steerable antenna.
- Small errors in the element primary beam shapes and the antenna pointings are not major sources of systematic errors.
- By appropriate design of the *uv*-plane weighting scheme, very accurate beamsize equivalence at several bands can be achieved. Experience with interferometers and with single dishes has shown that, even though one can always smooth a high-resolution image to lower resolution, when making precision observations there is no substitute for instruments which themselves have the same observing beams.
- Interferometers give zero response to DC atmospheric signals and the 2.7 K CMB.
- While co-mounted interferometers can have problems due to ground pickup, these can be eliminated by switching between a number of fields as they successively pass through a small range of angles relative to the ground, and/or introducing a third axis of rotation about the optical axis, and stepping the instrument through a number of parallactic angles, which has the effect of preserving the phase of objects within the field of view, while scrambling the phases due to the ground signal.
- Signals from other parts of the sky (e.g., Sun, Moon, Galaxy, ground emission) are strongly suppressed by the interferometer fringe rate and can be filtered out.

3.3 Implementation of coherent detectors

As pointed out above, the availability of gain and the preservation of phase in the device defining the noise temperature allows multiple copies of the full incident signal to be produced and used to measure the properties of the incident radiation without further noise penalty. This ability opens up a variety of signal processing and instrumentation approaches. We list here some of these possibilities, as well as some practical considerations in the implementation of coherent detectors.

- *Control of systematic errors*—There are many possibilities. The "science data channel" can have a null signal. Baselines and offsets can be made small and stable. The desired signal (e.g., polarization state, incident angle, intensity, frequency, phase) can be rapidly and appropriately modulated, strongly suppressing undesired and competing signals that may be present in the instrument or environment, giving excellent control of systematic errors. The signal can be processed by circuitry (e.g., polarization diplexers, quadrature hybrids, magic-tees, in-phase power splitters, phase delay/modulators) before power detection. This ability to encode the desired properties of the signal fields and subsequently look for correlations is a powerful tool for obtaining precision control over systematic effects. In a single-mode coherent system, each incident mode (e.g., a given polarization state) can be independently processed.
- *Spectral resolution*—Heterodyne techniques make it straightforward to achieve resolution $R = 10^8$, high enough to resolve essentially any spectral feature in astrophysics, Earth science, or planetary science.
- *Multiplying interferometry*—This has been discussed above.
- *Dynamic range*—Coherent systems based on amplifiers have good linearity over a large range of input signal levels. The same devices and designs can be used over a broad range of conditions. This facilitates design and testing and simplifies accurate calibration.
- *Operating temperature and testability*—Physical temperature requirements for minimum noise in amplifiers are presently around 20 K. Amplifiers work over a broad temperature range from above room temperature to well below 4 K. The system noise properties degrade gracefully as detector physical temperature increases above 4 K. Amplifier systems designed to operate cryogenically down to 4 K can be checked out and tested well at higher temperatures.

- *Cosmic rays and microphonics*—Cosmic rays produce no detectable disturbance in the output signal of amplifiers. In general, transistors are insensitive to vibration.
- *Filtering*—The presence of in-band gain lowers the overall filtering requirements to limit the influence of out band response.
- *Time constants*—Amplifiers are extremely "fast," i.e., the time constant of the transistors themselves is basically 1/bandwidth. Readout circuits can be designed to realize as much of this speed as needed.
- *Integration into arrays*—Cost-effective techniques for building large arrays of amplifier detectors have been demonstrated. Signals can be digitized in the cryogenic stage. Thermal design issues for arrays are not difficult.
- *Complexity and industrial infrastructure*—Transistors and other key components of coherent systems (e.g., phase switches, detector diodes, mixers) are solid state devices complicated to fabricate and complicated to understand. Fabrication facilities are extremely expensive, and process variations can mask design improvements, complicating the development process. On the other hand, amplifiers are the detector of choice for communications and remote sensing applications in the commercial and military world up to frequencies of several hundred gigahertz, at least. Significant synergies exist. This substantially decreases the size of the investment in technology required to realize the best cryogenic performance.
- *Quantum noise limit*—There is a lower limit to T_{sys} for coherent receivers set by quantum fluctuations.
- *Power dissipation*—Amplifiers dissipate significant power, milliwatts per transistor, in general. Good progress has been made in reducing this power dissipation over the last two decades, but when arrays of hundreds or thousands of elements are considered the total power dissipated is measured in watts. Cooling in space is not as hard as it used to look—for example, the 20 K cooler on *Planck* has shown that heat lifts of watts at 20 K are feasible at high efficiency—but it can be a driver of spacecraft design.
- *Arrayability*—Coherent amplifier arrays have not yet reached the levels of large-scale integration on single wafers that have been achieved, for example, with bolometers.

For high resolution spectroscopy and interferometry, coherent detectors are the obvious choice. Equivalently, for low resolution spectroscopy and continuum observations at submillimeter/far infrared wavelengths, direct detectors such as bolometers, not subject to quantum noise, are the obvious choice. In other areas, for example, CMB polarization, the choice is complicated. We will not make a detailed comparison of MMICs and bolometers for this use, but emphasize that comparisons should be made on the basis of total system performance and cost, in the relevant operating environment. Performance characteristics that must be considered include frequency range, sensitivity, systematic errors, linearity, lifetime, cryogenics, and requirements on the test environment. Ingredients of these performance characteristics include gain stability, bandpasses, time constants, cosmic ray response, temperature stability, power dissipation, required test environment, and many others. *Planck*, now flying, will provide for the first time much useful information on the performance of both bolometers and cryogenic amplifiers in space, as well as on foregrounds and the required frequency range for CMB polarization measurements. Sub-orbital polarization experiments in progress and planned will give valuable insight into how detectors/experiments behave at the extremely low integrated noise levels that will be needed. With this information in hand, a choice can be made.

4

Science Enabled by Large Coherent Arrays

This chapter presents some of the breakthrough science that will be enabled by large arrays of coherent receivers, and describes some conceptual designs for possible instruments. The discussion is divided into four areas: cosmology, astrophysics, Earth science, and planetary science. Throughout the chapter we identify the technical advances that are needed to enable a new generation of instruments in each of these areas. In the following chapter (Chapter 5) we will present a summary of these technological requirements.

4.1 Cosmology

In this section we highlight two fields that are currently at the frontiers of cosmology and astrophysics: (1) Measurements of the polarization of the microwave background radiation; and (2) Mapping clusters of galaxies via the Sunyaev-Zel'dovich (SZ) effect. These topics illustrate some of the requirements and challenges of arrays of receivers.

4.1.1 CMB polarization

Science from CMB polarization

The cosmic background radiation (CMB) is a relic of the early universe. It has a blackbody spectrum with an effective temperature of 2.725 K, and is almost perfectly isotropic. But in different directions it shows variations in temperature of a few tens of microkelvin and variations in polarization of about 1 microkelvin. Measurements of these fluctuations have enormously increased our understanding of the history and composition of the universe. The angular power spectrum of the fluctuations[1] holds a remarkable wealth of quantitative information about the early universe, and provides one of the foundations of our current model of the history of the universe (e.g., Spergel et al., 2003) .

Recently several experiments have detected the polarization of the CMB and made the first measurements of its angular power spectrum. The polarized CMB radiation can be decomposed into two components, called the E- and B-modes (e.g., Zaldarriaga & Seljak, 1997). These are analogous to the curl-free

[1]The angular power spectrum C_ℓ is a measure of the fluctuation power at different angular scales. Higher values of the multipole number ℓ correspond to smaller angular scales, $\theta \sim 180^\circ/\ell$.

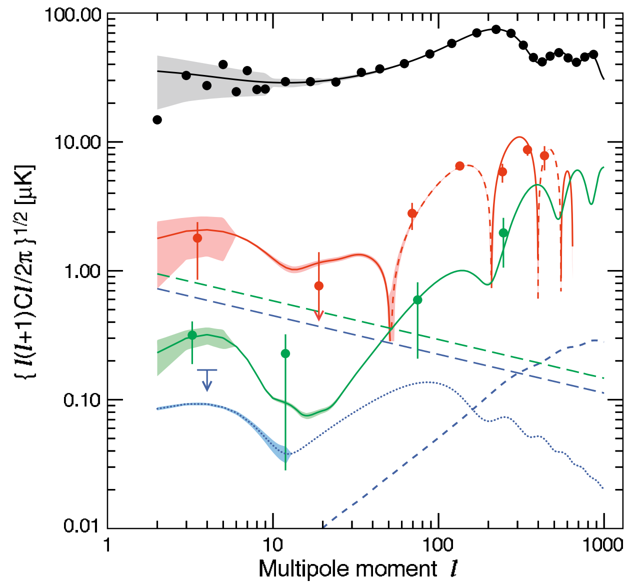

Figure 4.1: The angular power spectra of the various CMB components. Shown are the TT (intensity, black), TE (red), EE (E-mode, green solid), and BB (B-mode, blue dotted) modes (assuming a tensor to scalar ratio of 0.3). Also shown are the expected level of foreground contamination (long dashed lines) and the expected B-mode from gravitational lensing (short dashed line). From Page et al. (2007).

and divergence-free parts of a vector field respectively. The E-mode is mostly due to (scalar) density fluctuations in the primordial fluid, while the B-mode is a direct tracer of gravitational (tensor) waves from the inflationary period of the universe.

Characterizing the large angular-scale B-mode of the CMB is a major goal of modern cosmology, recently reviewed by the DoE/NASA/NSF interagency task force on CMB research (Bock et al., 2005)). Knowing the shape and amplitude of the B-mode power spectrum will allow us to distinguish between the suite of inflationary models allowed by theory, and provide new information about the epoch of inflation. As shown in Figure 4.1 the cosmological B-mode (blue dotted) signal has two components: the "reionisation bump" at $\ell < 10$ generated during the epoch of reionisation at $z \sim 10$, and a signal generated at recombination ($z \sim 1000$) at $\ell = 10$–100. The level of the B-mode signal is much smaller than the E-mode even for high values of the tensor-to-scalar ratio, r. As a consequence of this, although raw sensitivity is obviously important, control of systematic errors will be the critical factor in reliably measuring B modes (e.g., Hu et al., 2003; MacTavish et al., 2008).

A further vital consideration is the removal of foreground contamination. Galactic synchrotron and dust emission are polarized and their effects will have to be removed through spectral discrimination. In addition, gravitational lensing of the CMB by the large scale structure in the universe will convert E-mode into B-mode polarization and this contamination must be removed by measurement at $\ell \sim 100$–1000. Although this gravitational lensing B-mode is usually considered in terms of the contamination it introduces to the cosmological B-mode signal, it does contain a wealth of information which can be used to constrain cosmological models.

CMB observations have been made with bolometer arrays and with arrays of HEMT amplifiers configured as both interferometers and focal-plane arrays. Here we present conceptual designs for two possible next-generation instruments using MMIC amplifiers: a space-based focal plane array, and a ground-based interferometer.

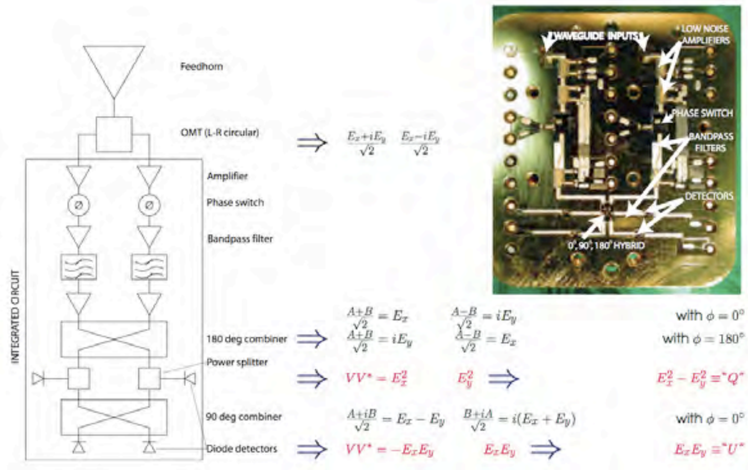

Figure 4.2: Block diagram of a pseudo-correlation polarimeter that measures Q and U simultaneously. MMIC receivers of this type have been used successfully in the QUIET experiment (see inset).

CMB-FPA: CMB polarization with a focal-plane array

Several concepts are under study for satellite-based instruments to study primordial inflation by measuring B-mode polarization, determine the ionization history of the Universe, and map the CMB polarization at large angular scales. Here we consider an instrument "CMB-FPA" based on HEMT amplifiers in MMIC receiver modules, and designed to be a low-cost option for a future space mission (target cost <\$350M).

Table 4.1: CMB-FPA: Number of feeds per frequency, power, and noise. Total N = 364, total power = 4 W.

Frequency [GHz]	N	Power [mW]	T_{rcvr} [K]	T_{sys} [K]	NEQU [μKs$^{1/2}$]	NEQU/freq [μKs$^{1/2}$]	4-yr Noise/1 deg^2 [nK]
30	4	4	7	10	81.6	40.8	750
40	50	7	8	11	87.0	12.3	230
70	160	10	10	13	77.7	6.1	125
100	75	12	12	15	75.0	8.7	200
150	75	15	20	23	93.9	10.8	500

Instrument Parameters Nominally observing for 4 years from an L2 halo orbit, CMB-FPA will observe in five frequency bands between 30 and 150 GHz. The focal plane will be filled with several hundred pseudo-correlation polarimeter MMIC receiver modules of the sort used in the ground-based QUIET experiment,[2] as shown in Figure 4.2. It will observe simultaneously in several frequency bands in order to facilitate foreground removal. The use of a MMIC array has the advantage that in a coherent (i.e., phase preserving) system, once the "quantum tax" is paid further processing adds negligible noise. In addition to highly effective suppression of $1/f$ noise and systematic errors, the simultaneous, continuous measurement of Q and U through one feed allows maximum efficiency in the use of valuable focal plane real estate. Table 4.1 gives the number of feeds per frequency, and the power dissipation and noise characteristics of the instrument. Preliminary indications from simulations of foreground separation suggest that the optimum way to divide precious focal plane real estate is to achieve roughly uniform signal-to-noise ratio on the total signal, that is, CMB + foregrounds. The noise and power values assume the latest 35-nm gate-length transistors (Kangaslahti et al., 2008), at a noise level about 2.5 times lower than currently

[2] http://quiet.uchicago.edu/

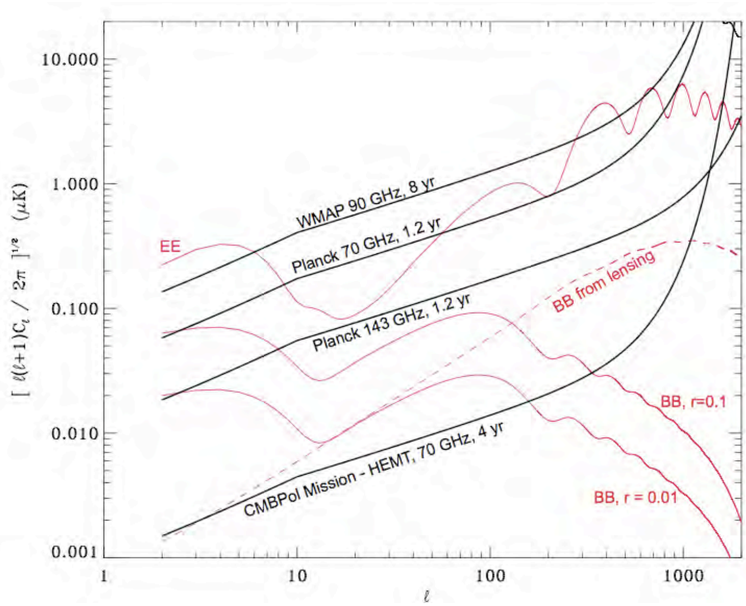

Figure 4.3: Comparison of noise levels in the 70 GHz band of the proposed CMB-FPA with *WMAP* at 90 GHz and *Planck* at 70 GHz (amplifiers) and 143 GHz (bolometers). B-mode power BB is plotted for values of the tensor to scalar ratio r, 0.1 and 0.01. The dashed curve shows the confusing BB signal due to weak lensing that peaks at about $\ell = 1000$. CMB-FPA (labeled as "CMBPol") is more than an order of magnitude more sensitive to polarization than *Planck*, and achieves the sensitivity to B-modes recommended by the CMB Task Force.

demonstrated. Based on past experience, several years of development effort could be expected to realize the great promise of these transistors, reducing the noise by a factor of 2.5. Figure 4.3 compares the performance of this instrument with that of *Planck*, and shows that subject to the usual assumptions about systematic errors and foreground separation it can reach the level of $r = 0.01$ recommended by the Task Force (Bock et al., 2005).

The most important technology development needed here is reduction of noise by the predicted factor of 2.5.

CMB-INT: CMB polarization with an interferometer

As discussed in Section 3.2.3, interferometers offer excellent control of systematic errors, which are likely to be the dominant design driver for a next generation B-mode experiment. Of particular importance in this regard is the fact that the shape of the synthesized beam can be calculated with high precision for an interferometer, based on the positions and detailed shapes of the individual feed horns. Beam-shape uncertainties are one of the most difficult types of systematic error to control for telescope-based CMB experiments, particularly in space. Small errors in mirror surfaces can have significant effects, yet there is no way to measure the post-launch, post-cooldown mirror surfaces directly, and there seem to be no polarized sources in the sky that are strong enough for direct beam mapping down to a low level, something that would be challenging for many hundreds or thousands of feeds under any circumstances. It remains to be seen whether beam uncertainties in telescope-based CMB polarization experiments in space are a fundamental limit or not. If they are, an interferometer with hundreds or thousands of individual elements might be the only solution. In the past, huge power requirements for digital correlators made contemplation of such an interferometer in space a mere fantasy. As we discuss in Section 6.4, however, those days are over. Dramatic progress in samplers and multipliers means that large space-based interferometers are feasible.

The utility and advantages of interferometers for observing the CMB polarization have been demonstrated by DASI (Kovac et al., 2002) and CBI (Readhead et al., 2004). The angular scale that we are discussing here for measuring B modes would be much greater, however, and a demonstration of the technologies involved on the ground is definitely necessary. We therefore consider a possible (and ambitious) design for "CMB-INT," a ground-based interferometer for measuring CMB polarization. CMB-INT would be an important step towards a follow-up space-based interferometer mission.

Instrument parameters To detect the B-mode of CMB polarization, CMB-INT will need to have excellent sensitivity to multipoles $l < 100$ along with the ability to measure out to higher l in order to measure and correct for the foreground B-mode signal introduced by gravitational lensing. This implies the use of close packed, small (few λ), comounted feeds as the interferometer elements (individual feed tracking in a close-packed array and on this scale is infeasible). This means that there is no astronomical fringe rate, but critically the exact knowledge of the synthesized beam remains.

Spectral discrimination would allow separation of the CMB from the polarized synchrotron and dust emission. We therefore envisage scaled arrays at 40, 90, and 150 GHz which will provide matched *uv*-coverage.

In order to achieve the required sensitivity, around 1000 elements will be required. However, rather than producing a single 1000 element instrument, we adopt a "foveated" approach where we optimize sensitivity to given angular scale sizes with a dedicated instrument. This approach has been demonstrated to work well with interferometers such as the VSA (Dickinson et al., 2004) and AMI (Zwart et al., 2008). We therefore envisage a 91 element, hexagonal close packed array as our unit telescope and instruments with 5λ and 15λ apertures, giving resolutions of approximately 1° ($\ell \sim 200$) and $20'$ ($\ell \sim 600$) respectively. The exact numbers of unit telescopes at each of the observing frequencies will need to be optimized through detailed simulations. Depending on the sensitivity achievable for each element, it may be desirable to sacrifice some surface brightness sensitivity by reducing the level of close packing and introducing some randomization in the element configuration, since this will improve the form of the synthesized beam.

The correlator requirements for CMB-INT will be demanding, but feasible (see Section 6.4). We would desire approximately 20% bandwidth at each frequency with around 1% spectral resolution. All the possible baseline pairs on each unit telescope would be formed, but we would not correlate the long baselines between different arrays. In addition, if there is a desire to measure the power spectrum below $\ell \sim 20$ (in order to look for the "reionization bump") then it may be possible to incorporate a total power receiver to measure these scales, which will otherwise be resolved out by the interferometer.

4.1.2 The Sunyaev-Zel'dovich effect

Science with the SZ effect

The Sunyaev-Zel'dovich (SZ) effect is a secondary anisotropy in the CMB due to inverse-Compton scattering of CMB photons by the hot (10^8 K) electrons in the plasma atmosphere of clusters of galaxies, the most massive gravitationally bound structures in the Universe. The surface brightness of the SZ effect is independent of redshift and so it allows observation of clusters back to their epoch of formation, beyond the range of X-ray observations. Galaxy clusters are fundamental components of the large scale structure in the Universe, so knowledge of their distribution and intrinsic properties has important implications for cosmology and the physics of structure formation. The SZ effect provides us with a powerful tool for finding new clusters, and for studying them in detail. Detections of clusters via the SZ effect are now routine (e.g. Birkinshaw, 1999; Carlstrom et al., 2002), but current instruments have relatively poor resolution. Recent X-ray studies by the *Chandra* and *XMM-Newton* satellites have revealed detailed sub-structure and complex temperature profiles. The physics of cluster atmospheres and cluster assembly is best studied by combining X-ray and SZ data, but SZ observations are currently unable to match the quality of X-ray imaging.

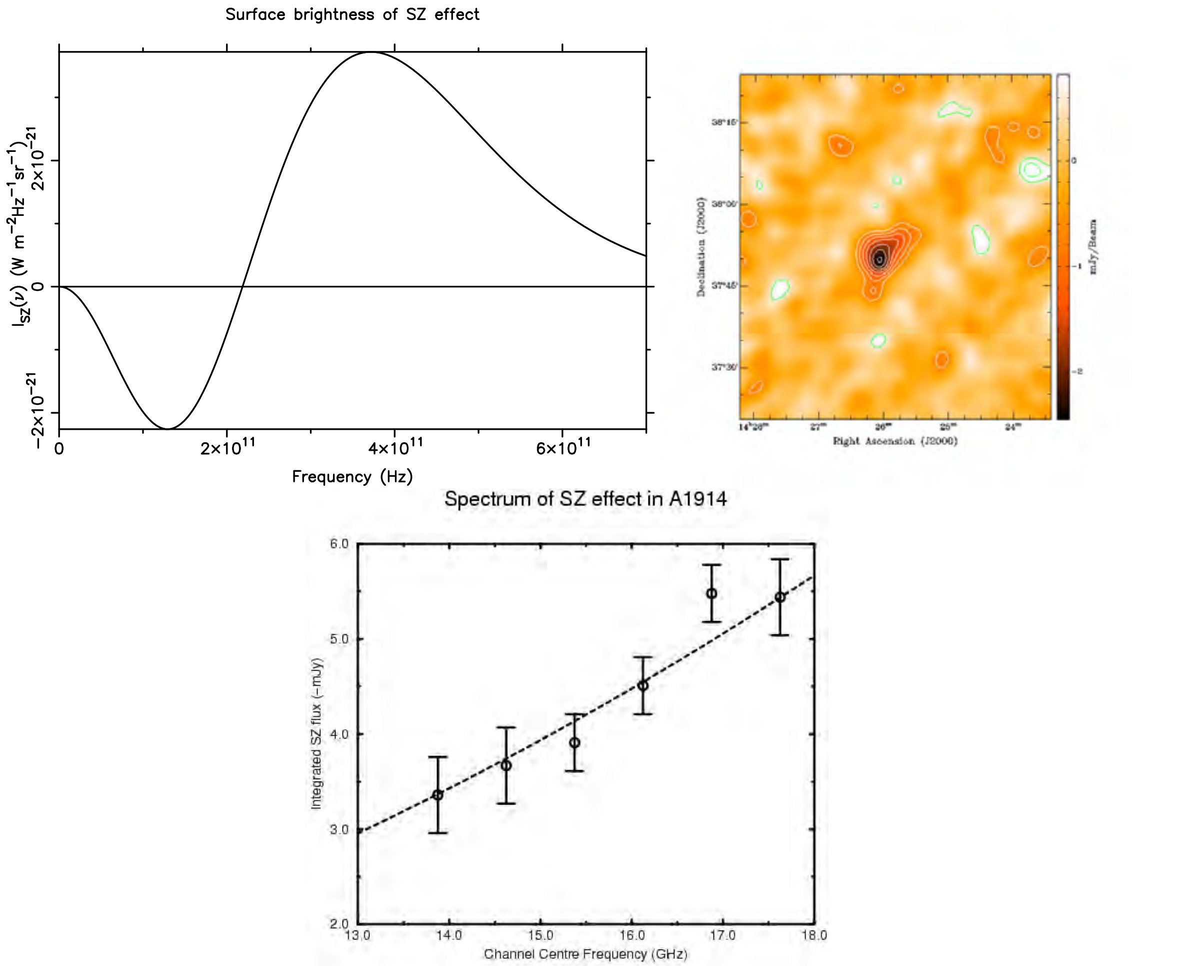

Figure 4.4: The spectrum of the thermal SZ effect. Map of the SZ effect towards cluster Abell 1914 measured in decrement at 15 GHz by the AMI telescope and the measured spectrum over a 56 square arcminute region at the cluster center (AMI Collaboration, 2006).

The primary or "thermal" SZ effect distorts the blackbody spectrum of the CMB (Fig. 4.4), creating an intensity decrement at frequencies lower than 217 GHz and an increment above. The effect is proportional to the line-of-sight pressure integral through the cluster, $y \propto \int n_e T_e \mathrm{dl}$ (where n_e is the electron density and T_e the electron temperature) and so provides complementary information to the X-ray surface brightness image, which has $\Sigma_X \propto \int n_e^2 f(T_e)\mathrm{dl}$, where $f(T_e)$ is a weak function of temperature. The electrons in the intracluster plasma are mildly relativistic and as a result the thermal SZ spectrum changes as the cluster temperature increases (Challinor & Lasenby, 1998). If this relativistic spectral distortion can be measured, then the mass-weighted temperature can be determined.

In addition to the thermal SZ effect, there is a "kinematic" SZ effect that is essentially a Doppler shift due to motion of the cluster along the line of sight. It has the same spectrum as primordial CMB fluctuations, so observations over a wide range of frequencies can separate the kinematic effect from the thermal effect, allowing cluster velocities to be measured. Cluster velocities are a valuabe probe of cosmological parameters and dark energy (e.g., Bhattacharya & Kosowsky, 2008).

SZIA: A Sunyaev-Zeldovich interferometer array

To illustrate the application of coherent receivers to the study of the SZ effect we consider a possible "Sunyaev-Zeldovich Interferometer Array" (SZIA). This SZIA is primarily intended for detailed studies of clusters rather than finding surveys. The *Planck* satellite is conducting the first all-sky survey for galaxy clusters since the *ROSAT* X-ray survey in the early 1990s: it is expected to detect 1000–2000 clusters, with ~ 200 at $z > 0.6$ and around 10 at $z > 1.0$. In addition, the South Pole Telescope (SPT) and the Atacama Cosmology Telescope (ACT) are conducting blind SZ surveys of large fractions of the sky and will detect thousands of clusters, with a larger fraction at high redshifts. In addition to its follow-up work, the SZIA will also be able to conduct small sky area, deep surveys for poor clusters and rich groups.

Instrument parameters To meet the science goals, an SZIA will need:

- Angular resolution comparable with new generation X-ray satellites—$10''$.
- Sensitivity to the outer regions of the cluster gas; so ability to map structure on $10'$ scales.
- Four or more frequency bands in the range 90–270 GHz, with similar resolution in each channel, in order to spectrally decompose the various SZ contributions and remove the effects of foregrounds and backgrounds (Knox et al., 2004).
- Some spectral resolution (around 1%) will be helpful for this spectral decomposition and in making precise images and calibrations.
- Low front-end system temperature. Currently SIS mixer arrays and HEMT IF amplifiers give approximately 35 K at 90 GHz and 45 K at 270 GHz: lower noise will reduce the collecting area required.
- At least 20 GHz of bandwidth at each frequency and as close to 20% bandwidth as possible at each of the observing frequencies.
- A high, dry site to minimize atmospheric noise.

Design considerations and technical requirements A single-dish antenna of sufficient resolution ($10''$ at 90 GHz) would be very large (60 m) and expensive. By contrast, an interferometer array offers many advantages, including scalability and excellent rejection of systematic errors. The resolution can be achieved with arrays of antennas, each with one or more coherent receivers. The technical requirements include low-noise, wide-band, coherent amplifiers at frequencies 90–270 GHz, low-cost steerable antennas with diameters ranging from 0.3 to 9 m, and low-cost digital processors to handle the correlation of many interferometer baselines with bandwidths of 20 GHz or more. Sensitivity is maximized with close-packed arrays (antennas separated by little more than their diameter).

A possible (ambitious) design for the SZIA would use several separate arrays to measure specific angular scales, e.g., at 90 GHz, 9 m antennas for $10''$–$40''$, 3 m antennas for $40''$–$2.5'$; and 1 m antennas for $2.5'$–$10'$. A close packed array with good filling factor can be achieved in each case with 10 antennas. To match resolution across the frequencies, smaller antennas will be used at the higher frequencies; and to ensure that the high-resolution arrays can cover the same area of sky as the low-resolution arrays, focal-plane arrays of feeds will be used in the high-resolution arrays. Ten antennas each of sizes 9 m, 3 m, 1 m and 0.3 m are required, with a total of 270 receivers at each frequency as shown in the following table.

Diameter	Number	Receivers per antenna			
		90 GHz	150 GHz	220 GHz	270 GHz
9 m	10	19	19	–	–
3 m	10	7	7	19	19
1 m	10	1	1	7	7
0.3 m	10	–	–	1	1

4.2 Astrophysics

4.2.1 The interstellar medium and star and planet formation

Study of the interstellar medium (ISM) in the Milky Way and other galaxies is fundamental for understanding key problems in astrophysics including:

- Star formation, including low and high-mass stars, clustering, the initial mass function, and the role of the magnetic field;
- Chemical evolution of galaxies;
- Formation of protostellar disks and planetary systems;
- Life cycle of the interstellar medium, including mass loss from evolved stars and the interface between different regions of the ISM.

This study requires determining physical conditions, chemical composition, and kinematics of gas in a wide range of environments. Of particular importance for the frequency range considered in this report is the dense, molecular phase of the ISM. This is where new stars and their accompanying planetary systems are formed. The molecular ISM is typically cold ($10\,\mathrm{K} \leq T \leq 100\,\mathrm{K}$) and has densities of H_2 molecules of 10^2–10^7 cm^{-3}. For these regions, spectral lines from a wealth of different molecular species at centimeter through submillimeter wavelengths are the most valuable probes.

The interstellar medium is spatially extended. To disentangle the various physical processes that determine its evolution, one needs to sample over a wide range of scales, i.e., one must image the ISM. High angular resolution is clearly important, especially when dealing with the environments of young stars and planetary systems, but interstellar clouds can be as large as 50 pc, subtending many degrees on the sky. On even larger scales, unraveling the large-scale structure of the Milky Way requires Galactic plane surveys covering hundreds of square degrees, with additional coverage required to study out-of-plane components such as high latitude clouds and high velocity clouds. Similar issues of large angular coverage combined with required high angular resolution apply to studies of the dense ISM in nearby galaxies, which can be up to many arcminutes in size (not even considering the Magellanic Clouds).

The molecular interstellar medium is rich in terms of chemical constituents and the range of chemical processes that contribute. The composition of the dense gas is critically related to the dynamical evolution of the ISM through molecular cooling and coupling to the magnetic field. The question of formation of complex molecules in the molecular ISM may be related to the origin of life. For these reasons, one needs to study the molecular interstellar medium in a variety of different species. Furthermore, to determine abundances accurately, multiple transitions of a given species are required.

Putting this together, we conclude that major advances in understanding the ISM will require:

- Large area maps of hundreds of square degrees with spectral resolution down to the sound speed;
- Images of the magnetic field intensity determined from measurements of the Zeeman effect;
- Multiple maps of different transitions of key tracers to determine densities, column densities, and abundances;
- Images of nearby galaxies in various tracers (tens of arc minutes in size) with velocity resolution of a few km s^{-1};
- The ability to measure redshifts and line widths of galaxies throughout the universe.

Some examples of possible "key projects" include the following. We emphasize that the scope of these investigations goes far enough beyond what has been done to date that surprises of many types can be anticipated.

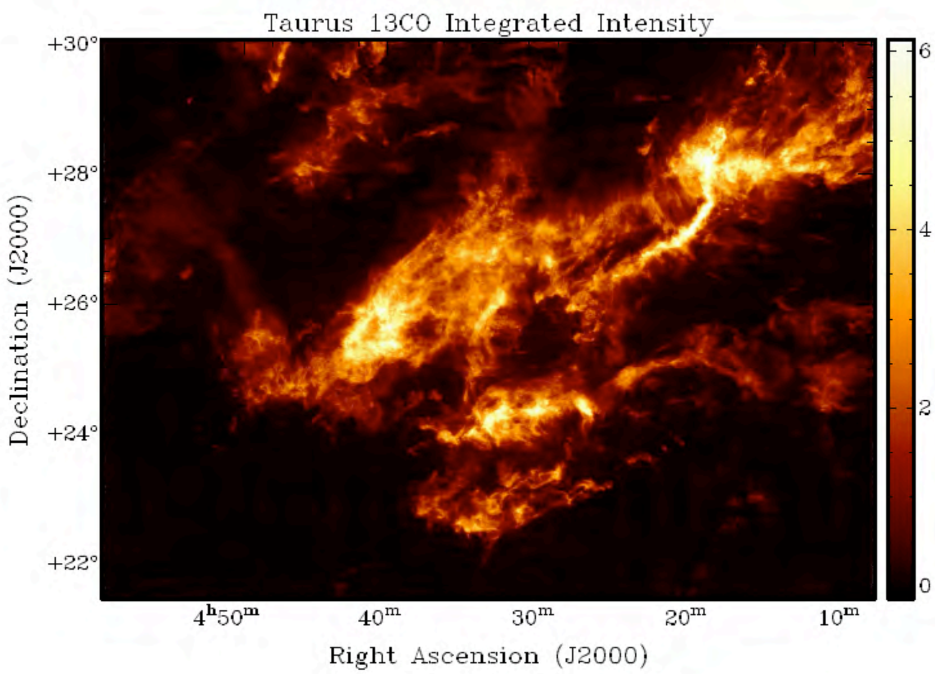

Figure 4.5: A 100 square degree region in the center of the Taurus Molecular Cloud, showing the integrated intensity of ^{13}CO $J = 1$–0 emission. The data were obtained with the SEQUOIA 32-element focal plane array on the 14 m Five College Radio Astronomy Observatory (FCRAO) millimeter telescope. The angular resolution is 50$''$ and the map is Nyquist-sampled with 20$''$ sampling interval, including approximately 3×10^6 pixels. The total time required was approximately 700 hr, as compared to the $\sim$ 20,000 hr that would have been needed with a single pixel receiver. A critical element of this image for understanding the structure of molecular clouds and star formation that takes place within them is the large spatial dynamic range (image size/sampling interval) which shows large scale organization of small-scale structures. This would be lost with either a large area map obtained with low angular resolution, or a small map obtained with high angular resolution. To cover the same area with $\sim$ 7 times higher angular resolution (50$\times$ smaller pixels), e.g., with the GBT, would require $\sim$ 50 times longer (35 000 hr) with the same array, but could be obtained in the *same* time (700 hr) with a 1500-pixel array.

- Complete maps of nearby star forming regions with resolution of a few arcseconds covering $\sim$ 100 deg^2 in $\sim$ 20 tracers, including CO, ^{13}CO, C^{18}O, CS, HC$^+$, HCN, and HNC. These species are essential for determining mass, kinematics, structure, and very importantly the relationship to the lower-density ISM and the magnetic field. These maps will form the basis for vital statistical analyses and comparison with theoretical models of molecular clouds, astrochemistry, and star formation.
- Images of the Galactic Plane ($0° \leq l \leq 360°$; $|b| \leq 2°$) in several key tracers, with wider latitude coverage in the region of the Galactic Center. The angular resolution and coverage are to be comparable with surveys from the *Spitzer* and *Herschel* satellites.
- Images of a large sample of starless and star-forming dense molecular cores in tracers yielding temperature, density, electron abundance, and other key parameters. Some of these can be done with a single transition (e.g., ^{12}CO for temperature), but some (e.g., density) require a minimum of two transitions.
- Images of line-of-sight magnetic field strength in cloud cores and envelopes obtained through Zeeman measurements of CN and possibly other lines. These observations require a dual-polarization system and many hours of integration per pointing, but yield unique information on cloud evolution and star formation.

- Fully-sampled images of ~ 100 nearby galaxies in a good set of tracers to probe physics and chemistry, and kinematics. These sources are a few to many arc minutes in extent, and are therefore difficult to observe with the ALMA array, which has a field of view $< 1'$.

Technological requirements

A large radio telescope or interferometer is required to achieve angular resolution of 20″ or higher. The requirements on angular coverage, the variety of species observed, and the weakness of some of the lines to be studied demand large-format focal plane arrays. While the exact specifications are yet to be determined, some of the key requirements are the following:

- Arrays having 10–1000 pixels.
- Performance per pixel may suffer only modest degradation over an optimized single pixel detector (i.e., state-of-the-art SIS receiver).
- Frequency coverage of the full atmospheric window.
- Instantaneous frequency coverage would ideally include the entire window or array range, although multiple windows of more modest tunable bandwidth would still be useful.
- Velocity resolution of 0.1 km s^{-1} for study of individual clouds, and 1–10 km s^{-1} for studies of the Galactic Plane and nearby galaxies.
- Dual polarization for Zeeman observations.

The key projects need to be examined in more detail and the required observations defined more precisely. This work will determine the requirements for the arrays. In particular, examination of the key science projects will determine:

- Which atmospheric windows are needed to answer the scientific questions (either the 3 mm or 1.3 mm window, or both).
- The preferred telescope for deployment, given the desired frequency band and required spatial resolution (e.g., GBT, LMT, Sardinia radio telescope, IRAM 30 m).
- The pixel count necessary given the required imaging speed, spatial resolution, telescope quality, and site performance.
- Instantaneous IF bandwidth, tuning bandwidth, and spectrometer configuration.
- MMIC or SIS technology for 3 mm or 1.3 mm band.

Strawman experiment

As an example, we may consider an ambitious strawman instrument based on MMIC amplifier technology, operating from 85 GHz to 115 GHz, which could be used on any of the above radio telescopes. The specifications presented serve to illuminate some of the possible technological challenges faced by such an instrument.

- 1000 pixel W-band focal plane array with $T_{\mathrm{rx}} \sim 20$ K.
- Dual polarization operation.
- 85–115 GHz simultaneous frequency coverage.
- I-Q downconversion to ∼0–15 GHz IFs covering 85–100 GHz and 100–115 GHz on the sky.
- Simultaneous processing of all 30 GHz of IF bandwidth at 0.1 km s^{-1} spectral resolution (30 kHz spectral resolution), with binning to lower resolutions, and digital sideband separation.

Such an instrument would require technology development in several areas:

- W-band low noise amplifiers require reduction in noise by $\sim$ 50% to equal the noise of current state-of-the-art SIS receivers.
- Manufacturable feedhorns, planar OMTs, Schottky I-Q downconverters with LO sources, and distribution and integrated IF processor components are all vital components.
- Carefully engineered packaging and large-scale integration is necessary to realize kilopixel arrays. Integration of the OMT, LNAs, and IF downconversion into mass-producible multi-pixel modules will be required. Wafer scale integration may serve to dramatically simplify the architecture of such an instrument.
- Development of advanced cryogenic and room temperature multi-conductor interconnect technologies for LO, IF, and DC signals.
- A spectrometer capable of processing $\sim$ 30 GHz of IF bandwidth, with 10^9 frequency channels. If this turns out to be too ambitious, the requirement could be relaxed to about eight 0.5 GHz bandwidth windows per pixel ($>$ 1350 km s^{-1}), tunable over the 30 GHz IF bandwidth. This would cut the bandwidth and channel number requirements for the spectrometer by a factor of $\sim$ 8, at the cost of increased IF processing complexity.
- All technologies must be cost-compatible with the construction of a reasonably priced instrument, i.e., $\sim$ \$10M at the time of construction.

4.2.2 High-redshift galaxies

Redshift machines

Some of the advantages presented in the previous section for MMIC front ends could also be exploited to develop a multi-object spectrometer for high redshift extragalactic astronomy. An important aspect of millimeter and submillimeter astronomy is the study of galaxies at high redshifts. These objects are likely to be identified first in large-area blind continuum searches, with follow up spectroscopic study of promising candidates to determine their redshifts. The density of these objects is modest, but with a relatively large telescope (e.g., the 25 m Cornell-Caltech Atacama Telescope, CCAT) there will be a few hundred per square degree at a reasonable flux level. This means that even a large field of view encompassing 0.1 deg^2 will include only a modest number of sources, so a conventional relatively close-packed array is not appropriate for taking advantage of the imaging capability of such a telescope; it would be sufficient to have $\sim$ 20 feeds positionable in a large (20′ diameter) focal plane.

For this application, the 190–300 GHz band is preferred due to the increased redshift range where at least two CO lines will fall within the spectrometer's bandpass. Ideally, such an instrument would cover the entire 190–300 GHz range simultaneously with no gaps, at a spectral resolution of 20 km s^{-1}. This resolution would resolve rather than just detect spectral lines, allowing study of the ISM in the detected sources. MMIC front ends could conceivably cover this entire atmospheric window. Following the MMIC gain stage, the 110 GHz bandwidth IF could be split and downconverted in several blocks. The spectrometer for such an instrument would require $\sim$ 400 000 channels.

A reconfigurable coupling system to position the limited number of receivers at the desired positions in the focal plane (analogous to those required for multiobject fiber-fed optical spectrometers) is needed. Goldsmith & Seiffert (2009) have developed a concept for an input optical system for a mm/submm spectrometer based on free space quasioptical propagation with reflective optics. The basic idea is to divide the focal plane into a number of "patrol regions." By actuating two rotations of a dual periscope beam waveguide coupling the signal from the specified region of the focal plane to a receiver, the entire patrol region can be covered. The size of the reflecting mirrors and overall system performance can be improved somewhat if one or more of the elements is a focusing mirror. The properties of the quasioptical input system then allow a conventional feed horn to illuminate the telescope optimally over a broad (up to 2:1) range of frequencies. The total loss (absorptive and spillover) should be less than a few percent,

Figure 4.6: The Combined Array for Research in Millimeter-wave Astronomy (CARMA) is a university-based millimeter array consisting of six 10.4-meter, nine 6.1-meter, and eight 3.5-meter antennas that are used in combination at millimeter wavelengths. Located on a high-altitude site in eastern California, CARMA provides unparalleled sensitivity, broad frequency coverage, sub-arcsecond resolution and wide-field heterogeneous imaging capabilities, along with innovative technologies and educational opportunities. CARMA conducts cutting edge scientific research and provides unique learning opportunities for the next generation of instrumentalists and astronomers. CARMA is operated by the California Institution of Technology, University of California Berkeley, the University of Chicago, University of Illinois Champaigne-Urbana, and the University of Maryland, with funding from the National Science Foundation and the member institutions.

and moderate cooling of the input optical system should make its contribution to the overall noise budget insignificant.

A significant improvement in noise from 1.3 mm-band MMIC LNAs and increased RF bandwidth will be necessary if a heterodyne system in this band is to be used. Finally, development of a downconversion scheme capable of downconverting the entire 110 GHz IF simultaneously will be needed. The development of lowest noise broadband HEMT MMIC amplifiers will, together with the low loss, reconfigurable quasioptical input optics described here, be of enormous importance for the full realization of the multi-object spectroscopic capability of a large telescope such as CCAT.

Interferometer arrays

Our knowledge of the millimeter wave sky at high resolution is still primitive, and large-scale maps with high point-source and surface-brightness sensitivity are vital for discovering new objects and establishing source counts for a variety of objects. In the near future, focal plane arrays on 50–100 m class single aperture telescopes will conduct large-scale maps of the millimeter-wave sky at approximately $10''$ angular resolution. Extending these surveys to an order of magnitude higher resolution will be vital to resolve molecular clouds in nearby galaxies, and to identify individual star forming sites over entire molecular clouds in the Milky Way.

For the foreseeable future, achieving $1''$ resolution at millimeter wavelengths will be possible only with interferometers. However, current interferometers are limited to small fields of view ($\sim 1'$), and cannot map large areas of the sky to an appreciable sensitivity and image fidelity. But the wide-field surveys that are needed to explore the full diversity of galaxies and young stars, and to complement wide-field optical and near-infrared surveys, would be made possible if focal-plane arrays were installed on interferometers such as the Combined Array for Research in Millimeter-wave Astronomy (CARMA)[3] (Fig. 4.6). CARMA is planning to implement new 3-mm MMIC-based receivers in the near future, followed by a 9-element focal-plane aray in each antenna, which will make it a powerful mosaicking instrument.

[3]`http://www.mmarray.org/`

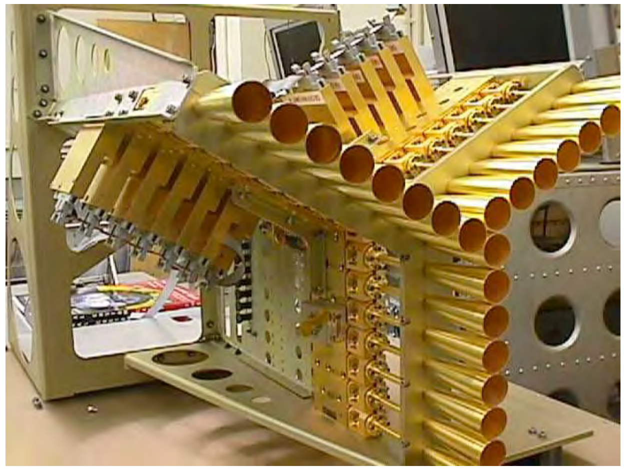

Figure 4.7: GeoSTAR consists of an array of microwave receivers. A prototype version of the sensor has been developed based on technology that could be scaled up to a flight version. GeoSTAR is a Fourier synthesis microwave spectrometer that measures atmospheric profiles by varying its spectral sensitivity and, hence, its depth of penetration into the atmosphere from above. GeoSTAR varies the horizontal location of the profiles, and thereby produces three dimensional imagery, by software beam steering of a large, thinned array of small antenna elements. GeoSTAR is able to produce full Earth disk 3-D images with no moving parts. The custom massively parallel integrated circuit in use in the GeoSTAR correlator was designed by the Center for Advanced Microelectronics and Biomolecular Research (CAMBR) at the University of Idaho.

4.3 Earth Science

Radio observations are fundamental to the advances made over the last fifty years in Earth remote sensing and weather forecasting. Measurement of the natural radio emissions from the Earth's surface, the oceans, and the atmosphere can be used to monitor rainfall, clouds, ocean surface winds, sea-surface temperatures, snowpack depth, sea-ice extent, ozone and other trace gases, and soil moisture, biomass, and vegetation distributions. Radio observations are essential for monitoring and understanding the processes leading to global warming. Some twenty or so satellites carrying passive microwave sensors are currently orbiting the Earth, contributed by the US and many other countries. The deployment of large arrays of receivers can improve sensitivity, angular resolution (spatial resolution on the ground), and time resolution.

As in radio astronomy, the arrays can be configured as focal-plane cameras, beam-forming arrays, or image-forming interferometers. Unlike in radio astronomy, background radiation from the warm Earth adds about 300 K of noise that limits the maximum sensitivity achievable.

The challenges for Earth science, and especially satellite remote sensing, are to make arrrays that are compact and light-weight, and have low power consumption. Cryogenic cooling to maximize receiver sensitivity is less important at low frequencies where even with warm receivers Earth radiation would still dominate the noise, and more important at high frequencies where noise from warm receivers would degrade sensitivity appreciably.

4.3.1 Science themes

Future drivers in Earth science are to resolve clouds and precipitation, resolve boundary layers, and characterize the surface of the Earth, clouds, and precipitation. These drivers require low-mass, low-power array systems (nadir sounders/imagers), low-power broad-band spectrometers (nadir sounders), low-noise receivers at 200 and 600 GHz (limb sounders), and correlation receivers.

The most challenging satellite measurements where array technology is relevant are in microwave atmospheric sounding from geostationary orbit. The near-term state of the art is represented by the Geostationary Synthetic Thinned Aperture Radiometer (GeoSTAR), a prototype instrument designed to observe and improve the understanding and forecasting of hurricanes, severe weather, and related hydrological-cycle processes (Fig. 4.7).[4] GeoSTAR will provide real time, continuous, three dimensional images of atmospheric profiles of air temperature and humidity from a geosynchronous Earth orbit. Operating near 50 GHz and 183 GHz, temperature and water vapor soundings at high temporal and spatial resolution will be provided for the first time.

The minimum performance requirements are to match what is currently available in low-Earth-orbit (LEO) with the Advanced Microwave Sounding Unit (AMSU). Placing AMSU-like measurement capabilities in a geostationary orbit (GEO) will enable a number of important applications, as discussed by the NRC for the "PATH" mission in its "Earth Science Decadal Survey," published in 2007. The most challenging aspect of the AMSU requirements is to obtain 50 km spatial resolution at 50–60 GHz for temperature sounding, which requires an aperture in the 5–6 m range. A real-aperture (RA) system of that size is infeasible, and that is the justification for a STAR system. Temperature sounding is also possible at 118 GHz, which could be implemented with a real-aperture system, but the atmospheric opacity there is too high to allow penetration to the surface under all weather conditions. Water vapor sounding is required at 183 GHz with 15–25 km resolution, and that can be done with either RA or STAR. In general, a STAR implementation is preferred over RA if either approach can be used, since a STAR has a clear future upgrade path while the RA does not.

Technological requirements

Receiver technology development needs range from the device level (low-noise MMICs) through module level (low-mass multi-receiver/chip modules) to instrument level (RF front-end to digital back-end integration).

The current state of the art in Earth science STAR systems is represented by the Soil Moisture and Ocean Salinity (SMOS) system launched by ESA in November 2009. This is not a sounder but an L-band (1.4 GHz) imager with $\sim$ 50 km resolution from LEO ($\sim$ 9 m aperture from a 73-element Y-STAR). The technology required for this mission is not particularly challenging, but the system concept is new for Earth missions and is therefore challenging.

The baseline GeoSTAR consists of a 3×100 element array at 50 GHz, equivalent to a 4 m aperture and 50 km resolution, plus a 3×200 element array at 183 GHz, equivalent to a 2.5 m aperture and 25 km resolution. Six spectral channels, which are required for sounding/profiling, are sampled with the 50 GHz array; and four are sampled with the 183 GHz array. The channels are sampled sequentially by rapid LO switching. Radiometric sensitivity is required to be better than 1/3 K per channel in a 15–30 minute period, which translates to about 3–4 min integration time per channel. Maximum allowed bandwidth per channel ranges from 200 MHz to 1 GHz.

The technology challenge for the initial GeoSTAR implementation is one of achieving baseline performance within reasonable mass and power limits commensurate with a medium-class satellite instrument, i.e., on the order of 200–250 kg and 250–400 W. The current state of the art is thought to be just sufficient to achieve this in time for a mission within the next decade, and therefore the "PATH" mission does not require additional breakthrough technology development. However, since the emerging technology is barely sufficient to meet baseline requirements, PATH will benefit from incremental advances in the next few years, which will result in performance margins.

[4] http://www.sprl.umich.edu/projects/GeoSTAR/

4.3.2 Sample mission: GeoSTAR-II

GeoSTAR-II (time frame 2020) will require very sensitive arrays of low-noise receivers if it is to meet its measurement requirements, tabled below.

Band [GHz]	Channels	Δx [km]	τ [minutes]	NEDT [K]
50–60	> 8	10	10	0.1
90, 160-183	> 6	5	5	0.1

In addition, the goal is to add 113–119 GHz and 325 GHz arrays.

The design concept to meet these requirements is to have two STAR arrays, of 3×500 receivers at 50 GHz and 3×1000 receivers at 183 GHz. To meet NEDT requirements without cooling, the receiver noise must be improved by a factor of 2.5 over current performance, or a more filled array with more elements will be needed. The 183 GHz correlator will have 12×10^6 2-bit multipliers at 10 GHz aggregate bandwidth.

Technology requirements

- Ultra-low-power, low-mass, low-noise receivers: This requires significant further development to MMICs at 183 and 325 GHz in array modules, fabrication and assembly.
- Ultra-low power digitizers and multipliers: GeoSTAR-II correlator needs may be met through technology evolution (Moore's Law: 10 years $\rightarrow 10^2$).
- Highly efficiency local oscillators and an efficient LO distribution scheme to reduce the system power requirements. A possibility would be development (10 year plan) for GaN oscillators and phase locking or injection locking. Multipliers and lower frequency (Ka-band) power amplifiers would also be required.
- Enhanced efficiency for the GeoSTAR 183 GHz receivers (600 elements) would reduce the power consumption and would benefit from the high efficiency W-Band GaN power amplifiers being developed at NGC.

4.3.3 Instrument: ACE

The Aerosol Cloud Ecosystems (ACE), a highly-ranked NRC Decadal Survey mission, has the primary goal of reducing the uncertainties about climatic effects caused by aerosol-cloud interactions and ocean ecosystem CO_2 uptake.[5] Interactions between aerosols and clouds are the largest source of uncertainty in climate models. Aerosols affect the formation and brightness of clouds as well as cloud precipitation, and they have been linked, for example, to decreases in rainfall in the Mediterranean. The increased uptake of CO_2 by the oceans causes them to acidify, leading, for example, to harmful algal blooms, which can affect the whole oceanic food chain. The ACE mission will study clouds and aerosols, and organic material in oceanic surface layers. It will enable the evaluation of the consequences of increased greenhouse gases and the effects of climate change on ocean ecosystems and food production, which will in turn allow the development of strategies for adaptation to climate change. It will also provide improved early warning of pollution events.

Instrument parameters

ACE will make simultaneous measurements of aerosol-cloud interactions with radar, lidar, a polarimeter, and a multiwavelength imager. The radar will operate at 34 GHz and 94 GHz. ACE or some other future

[5] `http://dsm.gsfc.nasa.gov/ace/`

Scanning Cloud 34 and 94 GHz radar, including possibly a 280 GHz radar system for enhanced science return, could be based on MMIC chips.

While the early studies have baselined extended interaction klystrons (EIKs) as the main radar power source to generate a 2 kW pulse at 94 GHz, several groups have worked on studies to use a solid-state electronically scanned phased array to generate the 2 kW pulse at 94 GHz. The power required to make such a phased array manageable (array size of 1000 elements or less) would be an output power of 2–3 W per power amp MMIC chip. The desired power-added-efficiency would be similar to that for Cloudsat (around 20% pulsed). With the advent of GaN W-Band power amplifiers at HRL Laboratories, 3 W/chip with 20% efficiency looks quite possible in the near term ($<$ 3 year development time). At 34 GHz, 5 W/chip or more has been demonstrated by several companies (Teledyne included), and there is no doubt that this is achievable in HRL's process as well, though multiple companies provide competition and hence reduce risk. Risk reduction is also a motivating factor for a solid-state phased array, as a single-point failure in a klystron would destroy the instrument, while a few failures in a 1000 element phased array would have a negligible effect on performance of the array.

In addition, a 280 GHz channel has been proposed for ACE and is part of a new Instrument Incubator Program at JPL. The program does not fund chip development, but rather an instrument study and prototype 280 GHz low noise receiver and power driver source.

Technology requirements

- MMIC GaN PAs, 95 GHz, $<$ 1 GHz bandwidth, 3 W/chip or greater under pulsed operation, 20% or better power-added-efficiency.
- MMIC phase shifters, possibly also of GaN, to allow electronic scanning of the array, with as low loss as possible.
- If 280 GHz PAs are possible using solid state technology, this would also be highly desirable. GaN development above 110 GHz remains largely unexplored in industry.

4.3.4 Instrument: SWOT

The Surface Water Ocean Topography (SWOT) mission[6] will carry out wide-swath altimetry for high resolution oceanography and hydrology. It is very highly ranked in the NRC Earth Science Applications Decadal Review (National Research Council, 2007). SWOT will measure how much liquid water is stored on Earth's land surfaces, and study its dynamics. It will explore how the hydrodynamics of inundated areas control the propagation of flood waves in major rivers, and what their implications are for regional and global carbon and other constituent fluxes. It will explore how the oceanic kinetic energy is dissipated, the small-scale (1–100 km) variability of ocean surface topography that determines the velocity of ocean currents, and how fronts and eddies are formed and evolve. It will also investigate the effects of coastal currents on marine life and ecosystems, and the implications for waste disposal. The societal benefits of SWOT will include a study of the quantity of water stored in the world's artificial reservoirs, its space-time dynamics, and the effect that freely available information about global reservoir storage will have on water management, particularly in trans-boundary rivers. It will investigate the dynamics of seasonally and ephemerally inundated areas and how these affect the propagation of disease vectors, such as malaria, and whether the capability to predict such dynamics can lead to the reduction of waterborne diseases. SWOT will also map ocean currents that are needed for shipping and throw light on the transport of pollutants, and analyze the effects of ocean eddies on marine ecosystems and fisheries, and in addition the data will be used toward possible improvements in hurricane forecasts.

A serious limitation of current profiling oceanic altimeters is that the 200–300 km spacing of successive orbital tracks prevents sampling of 2D currents and oceanic mesoscale processes that contain 90% of the

[6] `http://bprc.osu.edu/water/index.php`

kinetic energy. On the other hand, fresh water measurements are limited to *in situ* networks of gauges. SWOT will revolutionize oceanic and hydrology studies by providing the first global coverage with much improved resolution.

Instrument parameters

SWOT will measure the 1–100 km ocean surface topography that determines the velocity of ocean currents, and examine the variability of coastal currents and how these interact with the open ocean and the atmosphere, and the effects of these currents on marine life and ecosystems.

The SWOT altimeter must have a vertical precision of a few centimeters averaged over areas of less than 1 square kilometer. The suite of instruments that will be flown on the same platform includes a 15 GHz SAR interferometer, a 3-frequency microwave radiometer, a nadir-looking 15 GHz altimeter, and a GPS receiver.

This instrument uses a 35 GHz radar and would also benefit from a solid-state electronically scanned approach utilizing > 5 W per chip, $> 20\%$ PAE GaN power amplifiers and phase shifters to achieve a 2 kW pulse in Ka-Band.

4.3.5 Instrument: Earth imaging spectrometer

A future Earth spectrometer is desired to have a 72 GHz bandwidth, 1–4 MHz resolution, 150 W power consumption, and 25 kg mass.

The primary challenge is meeting the power budget. A rad-hard, 10 GHz bandwidth, 10 Gsps, 6 bit ADC is under development at Hittite (Phase II SBIR), but a substantial amount of additional funding (approaching $1 M) is needed to complete the development program and produce packaged chips. These would be good for 4 GHz bandwidth spectrometers, but 18 of them would be needed to cover a 72 GHz of IF, and at 10 W each the power goal would not be met.

Digital signal processing is similar to the situation with a planetary spectrometer—FPGA's are not well suited for handling this kind of signal bandwidth with any expectation of modest power consumption, but a rad-hard ASIC or structured ASIC will do the job with manageable power consumption.

Technology requirements

- Rad-hard ADC's with 6 to 8 bits of resolution, 12 GHz bandwidth, a sample rate of 25 GHz, an output interface that is easy to connect to an ASIC, and a modest power consumption of 12–15 W.

4.4 Planetary Science

4.4.1 Introduction

The millimeter and submillimeter wavelengths offer planetary science a unique opportunity to detect and identify polar molecules through their rotational spectra. Unlike shorter wavelengths where the vibrational and electronic bands of molecules are scattered over the spectrum, all polar molecules have a rotational band with an origin at zero frequency. As a result, a single millimeter and submillimeter instrument can detect and identify the entire chemical and isotopic content of the gas phase. Ideally the gas should be nearly Doppler limited (pressures less than 1 Torr). There are three classes of instruments: passive sounders, which measure a temperature difference between the line and a background; active sounders, which transmit and receive a signal to measure absorption directly; and *in situ* instruments, which illuminate a sample gas with a source to record the absorption. The primary science goals are: nearly complete characterization of the gas phase chemical composition (ppB range); determination of isotope ratios tied to specific molecular carriers; and detection and identification of complex organic molecules. All these require the instrument be re-configurable so that it can be used to cover a wide bandwidth. More instantaneous coverage is always preferable, but not at the expense of significant spacecraft resources.

Key science goals of limb sounding – requires significant atmosphere, e.g., Mars, Venus, giant planets, Titan. etc.:

- Chemical abundance and variability as a function of altitude, diurnal, seasonal and latitude. (Atmospheric mixing and chemistry).
- Vertical temperature and wind profiles.

Key science goals of passive and radar spectroscopy – requires tenuous atmosphere, e.g., Moon, Europa, Trition, Enceladus, Io, Callisto, Ganymede)

- Surface chemical composition due to sputtering process (ppm).
- Test of sputtering process (line shape, molecular excitation temperature).
- Magnetic field (requires oxygen or magnetic radical).

Key science goals of *in situ* measurement – requires access to the atmosphere or means of getting aerosol, liquid, or solid into the gas phase:

- Nearly complete characterization of the gas phase chemical composition (ppT range).
- Determination of isotope ratios tied to specific molecular carriers.
- Detection and identification of complex organic molecules.

Primary technological considerations for planetary instruments

Planetary instruments are often highly constrained by all spacecraft resources (mass, power, volume and cost). Additionally there are often stringent requirements on radiation hardness and lifetime. Due to the resource constraints, planetary instruments are generally single-pixel systems at ambient temperature, but they would benefit enormously from investments in integration for array systems.

Key technologies that could benefit planetary instruments include:

- Integrated low noise receivers (mixers will be used where LNA noise figure is above 10 dB, otherwise LNAs will be used with sub-harmonic mixer backends. Integration will need to include LO, Mixer and IF. *In situ* measurement will always use a mixer or a diode as the detector. Note that LOs will need highly efficient power amplifiers with active systems requiring significantly more power.)
  - Wide band, low noise amplifiers (preferably to 600 GHz).
  - Wide band IF amplifiers (a few gigahertz of bandwidth at a frequency of a few gigahertz).
  - High power-added efficiency power amplifiers for LO/transmit.
- Light weight antennas (a planar synthesized feed may solve many mass problems but is not needed for *in situ*).
- Low power digital spectrometers.
- Highly efficient radiation hard bias generation and distribution. It would be ideal to integrate with high frequency components but this is currently not advisable due to radiation.

4.4.2 Instrument: Planetary spectrometer

A future planetary spectrometer should have 4 GHz bandwidth with 0.1 MHz resolution. Its power requirement must be < 4 W, and its weight < 0.5 kg. The technology development needed to make this happen is a rad-hard 8–10 Gsps ADC with 4 GHz input bandwidth, 6 to 8 bits of resolution, and a power consumption of 3 W or less. Rad-hard 3 Gsps, 8 bit ADC devices from National Semiconductor that take 2 W are already available, but with only 1.5 GHz input bandwidth. Their 3 Gsps, 3 GHz bandwidth parts are impressive, but they say that there is no path to a rad-hard implementation for them.

The digital side of the spectrometer is not such a big leap. We could in principle use the latest rad-hard FPGAs from Xilinx (with some external rad-hard memory devices to enable a 32 768 or 65 536 channel implementation), but the power goal would not be met. The solution is a rad-hard ASIC for the digital back-end, but this is simply a question of funding—not a technical challenge.

Technology requirements

- Rad-hard 8 to 10 Gsps ADC with 4 GHz input bandwidth, 6 to 8 bits of resolution and a power consumption of 3 W or less.

4.4.3 Instrument: High resolution planetary landing radar array

Mars Science Lab will be flying a 5 element, 35 GHz landing radar instrument for its planned 2011 launch. Development of future, higher frequency landing radar instruments will enable capabilities not present in the current MSL baseline instrument, such as: higher precision altimetry and velocimetry measurements; much smaller antenna size for a 64 element T/R MMIC array than a 5 element 35 GHz array (about a factor of 5); reduced mass due to the more compact package; capability for hazard avoidance in more difficult terrain; and capability for precision landing.

Technology requirements

- MMIC low noise InP Amplifiers: Noise performance of LNAs < 8 dB ($T_{\mathrm{noise}} < 1540$ K); 20–40 GHz bandwidth; center frequency as high as possible up to 180 GHz.
- MMIC Medium Power Amplifiers: Transmit power 20 mW per element or better; 20–40 GHz bandwidth; center frequency as high as possible up to 180 GHz.
- InGaAs PIN diode SPDT switches. This would enable the system mass and volume to be reduced by a factor of two, if a low-loss switch could be used between the transmit channel and receive channel. Otherwise, separate transmit and receive antennas would be required increasing the mass and complexity of the system. While InGaAs PIN switches have been developed below 120 GHz, an SPDT switch has not been developed for this frequency range and bandwidth. Development of such a PIN SPDT switch would be enabling technology in addition to the LNAs and power amplifiers because system mass and volume are critical drivers for the inclusion of instruments on planetary spacecraft.

4.4.4 Instrument: Titan TCPRA

TCPRA (Titan Cloud Precipitation Radar) is a proposed Titan Orbiter instrument concept to measure the methane atmosphere using precipitation radar at 94 GHz, developed at JPL. Since planetary flight of a massive, high power extended interaction klystron (EIK) with mechanical scanning capability would be highly impractical, if not impossible, the study and hardware concept design involved the use of a solid-state MMIC phased array. Since this study, with the advent of > 1W/chip output power at 95 GHz using GaN technology, vast improvements to the complexity and power efficiency of such an instrument concept are now possible. The instrument goal is to have 1 kW pulsed power at 95 GHz.

Technology requirements

- High effiency power amplifiers with as high output power as possible over narrow (< 1 GHz) bandwidth, with a goal of 3 W per chip with 20% PAE.
- MMIC phase shifters, preferably compatible with the GaN technology, having low loss at 95 GHz for electronic scanning.

The above two items would enable the feasibility of a 300–400 element array for a planetary precipitation radar instrument.

4.4.5 Instrument: MIDAS/MDSUM

MIDAS/MSUM (Microwave Sounding Unit for Mars) is an instrument concept that would use a linear array of MMIC low noise amplifiers and mixers for measurements of 230 GHz CO and wind measurements.

Technology requirements

- Low noise (uncooled) MMIC amps at 230 GHz with noise figure < 5 dB ($T_{\mathrm{noise}} < 630$ K).
- Low DC power dissipation for a $\sim$ 20–30 element array.

4.4.6 Instrument: *In situ* (sub)millimeter wave

This instrument illuminates an absorption cell with a source to detect absorption. There are few reasons to operate above 600 GHz (unless the object is very hot and dominated by hydrides). For the detection of "biomarkers" (somewhat large organic molecules) the ideal range is 225–330 GHz at room temperature. At outer planet temperature this is shifted down to slightly lower frequency. Water and ammonia provide the reason to go to 600 GHz. The instrument will operate at ambient temperature (even if below room temperature) and mass and power will be driving issues. Schottky mixers are the most likely detector element since the figure of merit is the available dynamic range from detector noise floor to saturation of the IF.

Technology requirements

- Wide input band Schottky (the IF can be very narrow with the figure of merit being the IF saturation level).
- Widely tunable source (highly desirable to multiply up from < 20 GHz); highly efficient MMIC amplifiers.
- Integrated IF processing (LNA, filters, mixers, digitizers, digital signal processing).
- Highly efficient DC and bias electronics.

4.4.7 Instrument: Active sounding

This instrument illuminates the sparse atmosphere between a spacecraft and the surface with a narrow frequency radar pulse to detect absorption. Transmit power, detector noise figure and available aperture size dictate much of the sensitivity. The driving issues will be the mass and power required, especially since good performance is strongly tied to aperture size. This instrument will operate below 600 GHz with the best bands appearing to be below 200 GHz. The lowest noise detector at ambient temperature (possibly with some passive cooling) is desirable. Currently this means MMICs would be the choice below 360 GHz.

Technology requirements

- High PAE power amplifiers with power-saving pulsed operation and wide bandwidths.
- Widely tunable source (highly desirable to multiply up from < 20 GHz); highly efficient MMIC amplifiers.
- Broad band LNA for detection. Noise figure will be important.
- Integrated down conversion and IF processing.
- Highly efficient DC and bias electronics.

4.4.8 Instrument: Passive sounding

This instrument detects the brightness difference between molecular lines and the background. In general this leads to limb sounding (cold CMB background) or occultation (hot background, e.g., Sun, Jupiter, etc.). Since the beam is fully filled the sensitivity is given by the detector noise figure. Most desirable bands are 600 GHz and below for the same reasons as the *in situ* instrument; however there are a few important lines at higher frequencies. The detectors will be operated at ambient (or passively cooled) temperatures. Mass and power are the driving considerations.

Technology requirements

- Widely tunable source (highly desirable to multiply up from < 20 GHz); highly efficient MMIC amplifiers.
- Broad band, low noise receiver (LNA below 360 GHz; Schottky mixer above). Wide IF is useful and allows a trade-off between LO tuning and IF processing.
- Integrated down conversion and IF processing.
- Low-power correlation (more bandwidth is better but will trade bandwidth for low power).
- Highly efficient DC and bias electronics.

4.4.9 Applications of coherent array receivers

An understanding of the horizontal and vertical velocity fields of planetary atmospheres is important for the understanding of the redistribution of energy and chemistry within planetary atmospheres. This knowledge also supports a great deal of theoretical work that has be done to understand planetary circulation in general. In the thin upper atmospheres (< 30 mbar) of the planets, satellites, and the low density coma of comets, millimeter and submillimeter rotation-line spectroscopy provides a technique for the direct measurement of horizontal winds by measuring Doppler shifts of spectral lines.

Current techniques for measuring the winds using orbiting spacecraft are limited by the single-pixel instruments that are being used. For Earth, planet (e.g., Venus, Mars), and comet studies it would be beneficial to have imaging spectroscopic instruments that could be used to make these measurements simultaneously over large areas and pressure ranges. Linear spectroscopic arrays could be used to make limb sounding observations over large altitude ranges. Two-dimensional spectroscopic arrays could be used to extend the latitude range of the coverage and eventually lead to 3-dimensional composition, temperature, and velocity coverage. Nadir-looking imaging instruments can measure the distribution of clouds and humidity in Venus, Earth, and the giant planets.

5

Summary of Requirements and Commonalities

Table 5.1 summarizes the major receiver component and module needs and characteristics of coherent receivers that would enable the missions and experiments in cosmology, astrophysics, Earth science, and planetary science discussed in Chapter 4. Cosmology and astrophysics instruments require cryogenic receivers, amplifiers for front ends and IFs, and, where performance is better, SIS mixers with amplifier IFs. Earth and planetary instruments require ambient amplifiers for front ends and IFs, and, at high frequencies, ambient Schottky mixers with amplifier IFs. A high level of integration is required almost everywhere.

Table 5.1: Summary of Requirements

		Astro		Earth Sounding			Planetary			
Technology	Cosmo	Spec	THz	Limb	Active	Passive	Active	Passive	In Situ	Landing
Component										
Cryogenic LNA	•	•								
Ambient LNA					•	•	•	•		•
Cryogenic IF < 40 GHz		•	•	•						
Ambient IF <10 GHz						•	•	•		
Power Amp, high efficiency										
High power			•		•		•			•
Med power		•		•	•	•	•	•	•	
Multiplier, high efficiency		•	•	•	•		•	•	•	
Mixer										
SIS, wide IF		•		•						
High IF compression									•	
Schottky, low noise										
Schottky, high efficiency		•		•		•	•	•		•
Module										
Receiver, integrated	•		•	•	•	•	•	•	•	•
IF processor, integrated		•	•	•	•	•	•	•	•	•
Synthesizer, low power		•		•			•	•	•	
Spectrometer, low power digital		•	•	•		•		•		
Bias generation, integrated	•	•	•	•	•	•	•	•	•	•
Synthesized aperture					•	•	•	•		•

The missions and experiments identified in Chapter 4 vary widely in design and characteristics, and none could be built "off the shelf" at present. Nevertheless, the workshops identified a relatively small number of common technology developments needed across this broad range of instruments in order to realize the full promise of coherent instruments in space. We list them in rough priority order (rough because there is not a single axis for prioritization, and the goals are not all strictly independent), with the first two the most fundamental and the most general.

1. Reduce the noise levels of individual transistors and MMICs to three times the quantum limit or lower at cryogenic temperatures at frequencies up to 150 GHz.
2. Integrate high-performing MMICs into the building blocks of large arrays without loss of performance. Currently factors of two in both noise and bandwidth are lost at this step.
3. Develop high performance, low mass, inexpensive feed arrays.
4. Develop robust interconnects and wiring that allow easy fabrication and integration of large arrays.
5. Develop mass production techniques suitable for arrays of differing sizes.
6. Reduce mass and power. (Requirements will differ widely with application. In the realm of planetary instruments, this is often the most important single requirement.)
7. Develop planar orthomode transducers with low crosstalk and broad bandwidth.
8. Develop high power and high efficiency MMIC amplifiers for LO chains, etc.

In Chapter 6 we assess the current status of these key technology areas, and in Chapter 7 we set out a roadmap for their development. Before that, it is useful to consider the relationship between the technological needs of space science and those of commercial and defense users.

Historically, astronomy and remote sensing have adapted technology developed for other purposes, rather than driving the development itself. The basic technology of coherent receivers for radio astronomy and communications, for example, was developed primarily by the Department of Defense, but also by JPL/NASA with the development of maser receivers for deep space communications. In contrast, at submillimeter frequencies and for detectors such as bolometers that require extremely low temperatures, there are essentially no commercial or defense uses, and scientific users by necessity play the central role. Some of the technologies developed for other purposes but well-used in radio astronomy are large antennas, microwave components, transistors, MMICs, and computers.

This situation continues today. This is fortunate in many respects, because the development and fabrication of transistors, MMICs, digital signal processing chips, and related components is a huge, capital-intensive undertaking, requiring funding far beyond the levels of science. Interestingly, at present there is far more funding for commercial wireless communication technology development than even for defense electronics development. For example, a modern cell-phone contains "a digital receiver on a chip," comprising an antenna, a low-noise amplifier, an analog-to-digital converter, and a digital processor. This level of integration can presently be achieved at frequencies up to a few gigahertz, and would be feasible as the IF portion of MMIC array receivers in the terahertz region.

Yet a critical developmental role is still required of the scientific users of these technologies, who place the most stringest demands on performance. Achieving the absolutely lowest noise generally requires both cryogenic operation and careful adaptation of general technologies to meet specific requirements. Examples of this will be seen in Chapter 6, especially in two areas, cryogenic development of MMICs, and development of digital signal processing components. The capability of chips for digital signal processing processing has been increasing at a Moore's law pace for a long time, driven by commercial needs and a huge amount of money.

6

Technological Status

Transistor amplifiers and mixers (SIS at cryogenic temperatures for astrophysics, Schottky at room temperature for Earth science) have dominated the field of low-noise coherent detectors for decades. Especially at higher frequencies, SIS mixers have had the lowest noise. Compared to mixers, transistors have had broader bandwidth, greater dynamic range, and the convenience of cryogenic operation at 20 K rather than 4 K or lower.

Dramatic improvements in noise and power dissipation of transistors have been achieved over the last 20 years, with high electron mobility transistors (HEMTs) being fabricated first on GaAs substrates, then on InP substrates. Over the last few years operation above 700 GHz has been demonstrated, with room temperature noise at high frequencies a factor of two lower than before. Models based on this high frequency performance predict that cryogenic noise a few times the quantum limit should be achievable over a large frequency range.

Similarly dramatic advances have been made over the last few years in the packaging of amplifier receivers, making large arrays of receivers possible. Many of the same techniques are also applicable to mixer arrays. We discuss the state of both areas below, and identify technology development required to realize the kind of performance required for the science programs in Section 4.

Up to a few hundred gigahertz, SIS mixer noise has been close to the quantum limit for decades. Improvement in mixers is therefore focused on increasing bandwidth.

Complete instruments require more than just amplifiers or mixers, of course. The auto- and cross-correlators needed for spectroscopy and interferometry can be very large indeed. Until now, mass and power limitations have made large digital correlators impossible in space, thereby limiting severely the kinds of instruments that can be flown. Rapid changes in the capabilities of sampler and multiplier chips, however, driven by overwhelming commercial forces, have changed the possibilities dramatically.

In this section, we discuss the current state of key technologies at the device, "module," and instrument level, followed by consideration of digital signal processing technology.

6.1 Device level

6.1.1 Transistor and amplifier performance

In 2006, Northrop Grumman Corporation (NGC) developed a new ultra-short-gate-length high electron mobility transistor (HEMT) process[1] (Deal et al., 2006), incorporating the following changes:

[1]Funded in part by the DARPA Submillimeter Wave Imaging Focal-plane Technology (SWIFT) program, whose goal is room-temperature imaging arrays at submillimeter frequencies.

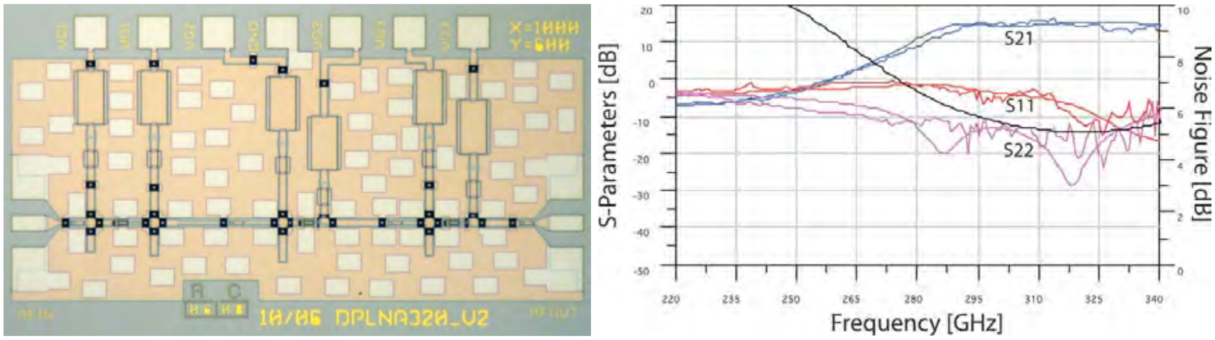

Figure 6.1: *Left:* Three-stage MMIC amplifier with 15 dB of gain over the frequency 285–340 GHz at room temperature. *Right:* Three-stage MMIC amplifier measurements and model of S21 (gain), S11 (input return loss), and S22 (output return loss). In each case, the smoother curve of the pair shows the model. Excellent agreement is seen between the measurements and the model. The black curve shows modeled noise figure (right-hand scale). The high frequency limit is set by the frequency range of the measurement, not the amplifier.

- Gate length reduced from 0.1 μm to 0.035 μm $\Rightarrow$ parasitic gate-source capacitance is reduced and cutoff frequency is increased by a factor of two;
- Ohmic metal and contact resistance reduced by a factor of two;
- InAs channel enabled through new epitaxy design $\Rightarrow$ improved electron mobility by 25%;
- 2-mil thick wafer process $\Rightarrow$ reduction of via hole size and pads by as much as a factor of 4, to support higher frequency designs;
- reduction of minimum line size and spacings by 30-40%.

Amplifiers using this technology give breakthrough performance up to 340 GHz at room temperature (Dawson et al., 2005; Deal et al., 2006, 2007; Gaier et al., 2007; Pukala et al., 2008; Samoska et al., 2008; Kangaslahti et al., 2008). Figure 6.1 shows a 3-stage amplifier with 15 dB of gain at room temperature. This design is the highest frequency amplifier reported at the time of the KISS workshops, and shows excellent correspondence between modeled and measured results.

A transistor model based on measurements on-wafer predicts that the 35 nm devices have a maximum stable gain (MaxGain) of 5 dB up to 600 GHz (Fig. 6.2), with 10–17 dB gain per stage predicted for 30–200 GHz under ideal circuit matching conditions.

The technology has demonstrated very low noise at these frequencies (Deal et al., 2006; Gaier et al., 2007), with a noise figure[2] of 7.5 dB at room temperature for a 270 GHz LNA (Fig. 6.3).

Cryogenic performance

The lowest noise is achieved with amplifiers cooled to cryogenic temperatures. Kangaslahti et al. (2008) characterized the noise performance of a three-stage MMIC amplifier for the 180 GHz band as a function of physical temperature (Fig. 6.4). At room temperature, the noise temperature at 160 GHz is less than 400 K, a factor of two smaller than the previous state of the art, with gain of $\sim$16 dB. At 30 K physical temperature, the noise temperature is < 100 K up to 170 GHz, the lowest cryogenic LNA noise temperature ever reported at these frequencies. These improved cryogenic results were obtained even though the amplifier showed a clear "kink effect" in its cryogenic DC I-V curves. This precluded proper biasing of the amplifier, thereby increasing its noise.

Over the last 20 years little change in noise has been observed below 20 K physical temperature; however, recent results from the University of Manchester (Richard Davis) suggest that for the latest devices

[2] *Noise figure* in dB is the standard measure of noise in the non-astronomical world. The correspondence between NF and noise temperature T, the astronomical standard, is given by $NF = 10\log\{T/290+1\}$, with T in kelvin.

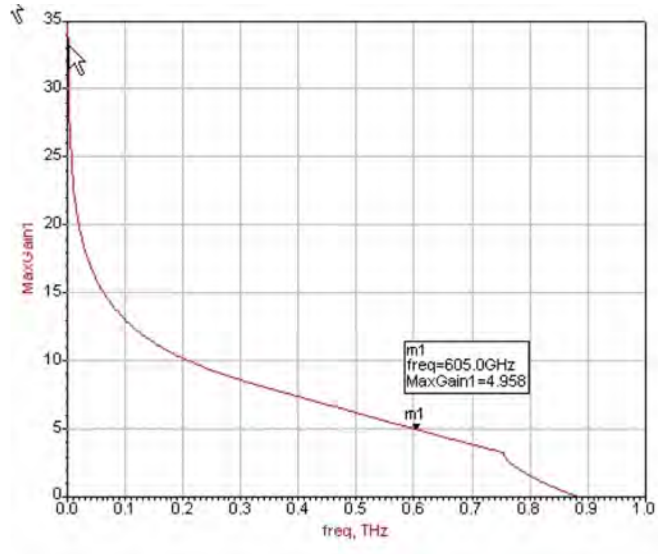

Figure 6.2: Predicted maximum available/maximum stable gain (MaxGain) of the 35 nm gate HEMTs. MaxGain is above 5 dB up to 600 GHz, and is between 10 and 17 dB for frequencies between 30 and 200 GHz.

noise continues to drop as temperatures decrease. This requires more investigation. For convenience here, though, “cryogenic” will mean $\sim$ 20 K unless otherwise specified.

In general, the noise of previous InP transistors (whether MIC of MMIC) decreased by roughly an order of magnitude from room temperature to 20 K. The factor of four measured for the 180 GHz amplifier is clearly less than a factor of 10, even allowing for the small additional reduction that would be expected between 30 K and 20 K physical temperature. One might worry that cryogenic performance is being limited in the 35 nm gate devices by some factor not previously seen in other devices. An even more recent measurement shows that this is not the case. Figure 6.5 shows the noise temperature for a W-band amplifier built by Eric Bryerton at NRAO cooled to about 15 K. From 300 K to 15 K the noise decreased by a factor of ten, showing that the 35 nm devices follow the trend of the best previous devices when they are cooled to cryogenic temperatures.

Noise models and predictions

The key question is how close can amplifiers be brought to the fundamental quantum limit, and what is required to get there? A more immediate question is what is the full cryogenic potential of the 35 nm gate devices now being produced? Their performance significantly exceeds anything seen before, judged by room temperature performance at frequencies up to $\sim$350 GHz and the first cryogenic measurements.

A theoretical answer to the second question can be given by a noise model of the new devices. For nearly two decades, the standard model of low noise transistor noise has been that of Pospieszalski (1989), which uses two noise sources, one on the gate and one at the drain of the device. These noise sources are obtained in practice by setting the physical temperatures of the R_g and R_{ds} to values that match the measured results. The correct temperature of the R_g is the physical temperature of the circuit (either 295 K or 20 K, depending on whether we model the room temperature or cryogenic performance of the amplifier). The r_{ds} models the drain noise of the transistor and is typically 15–20 times the physical temperature of the device, depending on the technology. Kangaslahti (private communication) has developed such a model, and with it he obtains a room-temperature noise figure of 3.3 dB for a single device at 270 GHz. If cascaded in a three stage amplifier with 11.5 dB of gain (assuming 1.5 dB losses in passives in each stage), this would translate to a noise figure of 6.7 dB for the amplifier in Figure 6.3, in good agreement with the measured value of 7.5 dB.

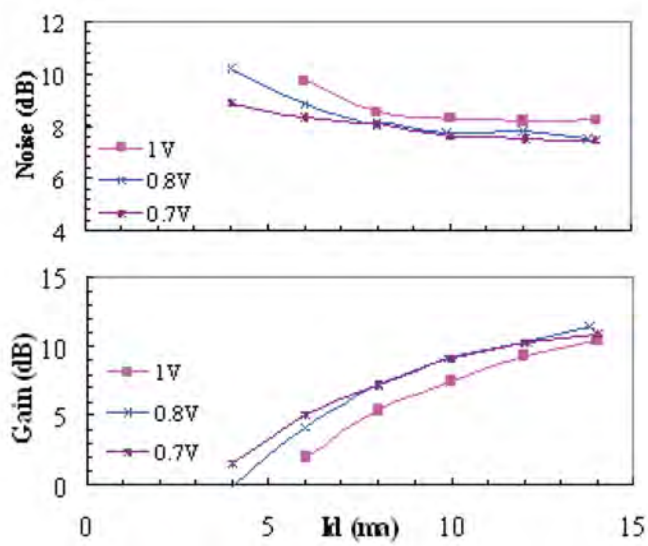

Figure 6.3: Measured noise figure and gain for a 270 GHz amplifier at room temperature. $NF = 7.5$ dB at maximum gain of 11.5 dB.

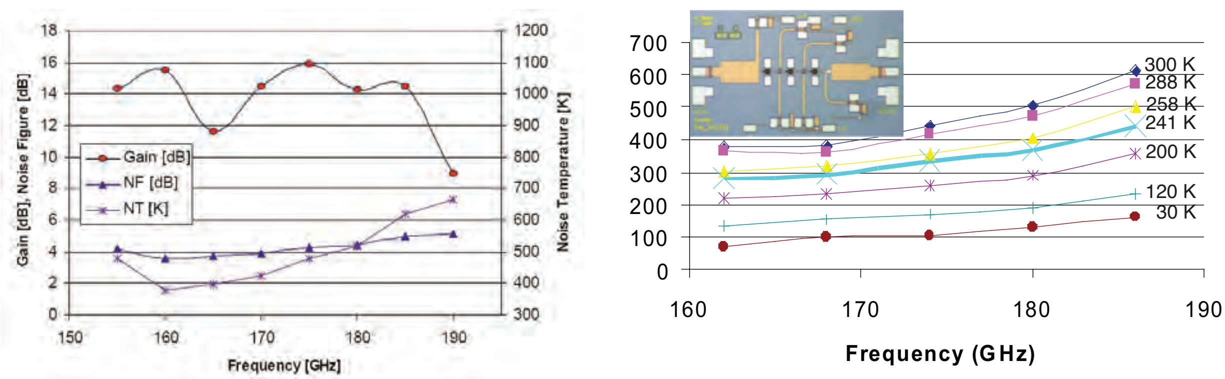

Figure 6.4: Measurements of 180 GHz amplifier (inset photo) at room temperature (*left*) and as a function of temperature down to 30 K (*right*). Noise is a factor of two lower than the best previous results at both room and cryogenic temperatures (Kangaslahti et al., 2008).

Using this noise model at 20 K gives the results shown in Figure 6.6, namely 7.9 K ($4q$) at 40 GHz, 11.5 K ($2.6q$) at 90 GHz, 19.5 K ($2.8q$) at 140 GHz, and 24 K ($2.9q$) at 165 GHz. All designs had more than 20 dB of gain, so these numbers would be very close to the final noise temperature of the actual receiver (i.e., later components in the receiver signal path would have little effect on the system noise). These design simulations are preliminary and not optimized. Although the predicted performance is still a factor of two better than measured for the amplifier in Figure 6.5, that was the very first W-band 35 nm amplifier measured cryogenically.

All of this suggests that **there is an excellent prospect of achieving noise levels of $\sim 2.5q$ over a broad range of frequencies, levels which only a few years ago seemed far off in the future.**

Summary

Recent progress in InP HEMT technology both in the exploration of new structures and further reduction of gate length from 80 nm to 35 nm demonstrates that the potential of HEMTs for broadband, extremely

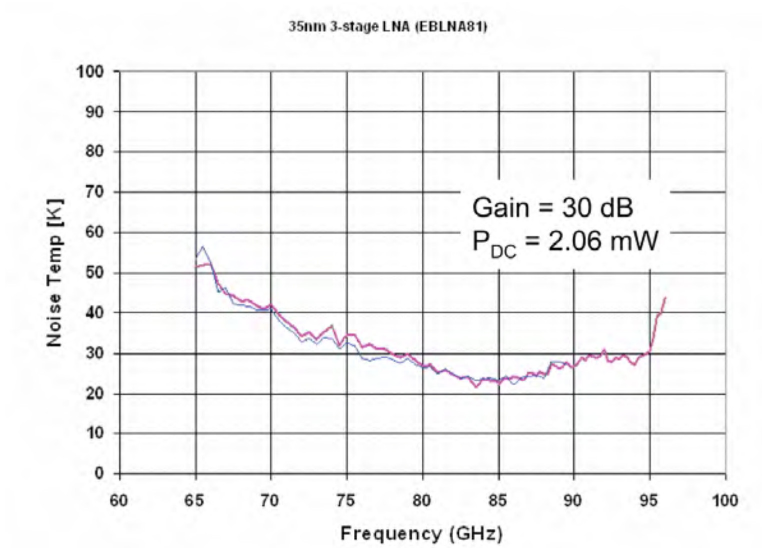

Figure 6.5: W-band MMIC amplifier cooled to $\sim 15\,\mathrm{K}$. The noise is the lowest ever measured for an amplifier at these frequencies, and an order of magnitude lower than at room temperature.

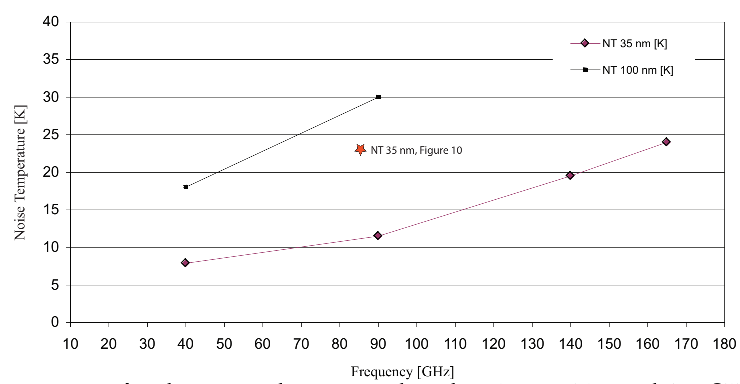

Figure 6.6: Noise temperatures for the 35 nm devices predicted at 40, 90, 140, and 170 GHz by the noise model extrapolating to lower frequencies and **cryogenic temperatures**. The improvement predicted over the best previous transistors (upper line in the plot) is dramatic.

low noise amplification, which would make possible a broad range of investigations at the forefront of cosmology, astrophysics, Earth science, and planetary science, is far from exhausted. Further research is likely to raise the frequency in which cryogenic HEMT noise performance is competitive with that of best SIS mixers from the current value of 100 GHz to about 200 GHz, with many advantages for large array receivers.

6.1.2 Mixers

SIS mixers are the most sensitive heterodyne detectors at frequencies above 200 GHz. They now routinely achieve noise temperatures close to the quantum limit at frequencies well below the superconducting gap of Niobium. For continuum work (e.g., CMB anisotropy), however, they are still less sensitive than bolometers as a result of the relatively narrow instantaneous IF band of the SIS receiver. Increasing the IF bandwidth, and being able to build large arrays, would allow SIS mixers to play an important role in new scientific exploration, both in spectroscopic and continuum source observations. A number of key problems have limited the IF bandwidth of SIS mixers to a small fraction of the frequency of the RF signal:

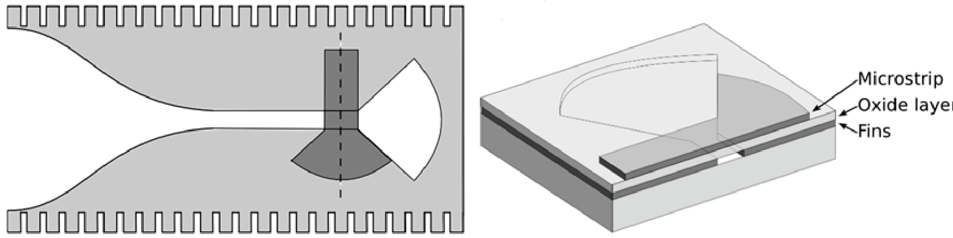

Figure 6.7: A 2–20 GHz IF bandwidth SIS mixer design by Oxford for 220 GHz.

- Since each of the sidebands has bandwidth equal to the IF bandwidth, the RF signal must be coupled to the mixer over a relatively large frequency range.
- The SIS junction must see a constant embedding impedance over the IF bandwidth.
- Signals at the highest IF frequency must be blocked from the RF transmission line.
- The IF output of the mixer must be matched to the IF circuit.
- Parasitics at the high IF frequencies must be mitigated.
- IF amplifiers with huge bandwidth, excellent noise temperature and excellent return loss must be developed.

In addition, SIS mixers are currently limited to frequencies below 1.2 THz. Investigation of new materials (such as BKBO, MgB_2) and fabrication refinement (for NbTiN) hold the promise of extending this upper frequency limit to $\sim$ 2 THz.

Many groups are working to extend the IF frequency bandwidth of SIS mixers. As an example, the Oxford group (led by Ghassan Yassin) is developing an SIS mixer centered at 220 GHz with an IF band from 2 to 20 GHz (Fig. 6.7). The chip will be fabricated using a finline transition from waveguide to microstrip. To prevent the IF signal from leaking into the finline transition, an RF bandpass filter is placed between the finline and the mixer tuning circuit. The filter is made of three sections of microstrip lines and two parallel capacitors in series. The parallel-plate capacitors are fabricated by depositing the lower plates as part of the first Nb wiring layer before anodizing the plates to form the niobium oxide. Tuning of the junction capacitance over a wide band is done using a single ended dual junction tuning circuit. The RF choke is made of six stepped-width sections of microstrip in series.

6.1.3 Power amplifiers

As we saw in Section 4, power amplifiers are needed in local oscillators and in radar systems.

Power amplifiers are needed for the local oscillators in both multi-pixel arrays and terahertz systems; the power amplifier is either directly in the LO signal chain or in the phase lock loop that is required for frequency calibration. In arrays, power amplifiers provide a simple solution for controlling the LO power to each receiver. A powerful LO is needed if MMIC LNAs are used since the down-conversion will be accomplished with diode mixers, each needing at least a fraction of a milliwatt of power. Saturated output power is less of an issue, but for the diode applications LO power will be a major consideration, especially at high frequencies $\sim$300 GHz. Generation of consistent sensitivity maps is critical, so equalization of LO power will be a significant problem in both CMB and astronomical spectroscopy.

There are several applications of power amplifiers in radar systems. One application is in the output stage of the radar; another is in a phased array feed, in which the beam is steered electrically rather than by changing the physical pointing of the antenna. There are also applications in landing radars where resolution and size are important.

6.2 Module level

6.2.1 Packaging of components

It is clear that as the size of focal plane arrays increases into the hundreds and even thousands of receiver elements, greater care and emphasis must be placed on packaging of components. The overall packaging design must take into consideration issues such as manufacturability, testability, reliability, flexibility, troubleshooting, size, weight, cost, and of course electrical performance.

A critical aspect of packaging design is selecting the appropriate amount of integration. Usually, this is driven by the tradeoff between manufacturability (demanding higher levels of integration) and testability (demanding lower levels of integration). Highly integrated receiver designs are typically smaller, lighter, and (in large quantities) cheaper; and they may even offer better electrical performance in situations where manufacturing tolerances are critical or where connectors or cable runs can cause problems.

However, failures of highly integrated modules are also far more difficult to diagnose. When only the global performance of an instrument or subassembly can be tested, it is not always clear where in the system a problem may lie when the performance is not as expected. The inclusion of externally accessible test points—in the form of weak couplers which can be used to sample the signal spectrum at different points in the RF path, for example—can alleviate some of this difficulty, but these test points must be incorporated with great care, otherwise they can easily nullify the advantages of size- and cost-reduction afforded by the integrated approach in the first place.

With this in mind, it is evident that high levels of integration require technologies with very good process stability and yield. The inherent non-repeatability of cryogenic transistor noise performance, for example, may prove to be a limiting factor in the level of integration that is practical for a given project. Similarly, manufacturing tolerances with high-performance electromagnetic components such as feed horns and OMTs may also play a crucial role in determining what level of integration is achievable. Consequently, any improvement in these technologies in terms of their reproducibility will be an enabling development in the area of large-format focal plane arrays, in which highly-integrated packaging will ultimately be a necessity.

The nature of the above concerns and the characteristics of the technologies involved dictate that different solutions will be preferred for arrays of different sizes. It is useful at this stage to review the current state of the art and preferred packaging solutions for arrays of different sizes, as determined by the best experience of world leaders in radio astronomy receiver design who attended the Keck Institute MMIC Arrays and Spectrographs Workshop.

One, two, or a few receiver elements

Usually arrays consisting of only a small handful of receiver elements, though they may be very sophisticated, can be built most quickly and cost-effectively using discrete, connectorized, and individually-tested components. Yield is not critical, and a relatively large amount of hand-tuning and element-by-element optimization is permissible.

Examples that fall into this category include most of the single-beam receivers currently in use on large single-dish telescopes such as the Green Bank Telescope. Exceptions to this category may include space-based applications where size and weight considerations may demand a higher level of integration than is otherwise warranted for so few receiver elements.

These design techniques are well-established and understood, and therefore are not an area of focus for the Keck Institute.

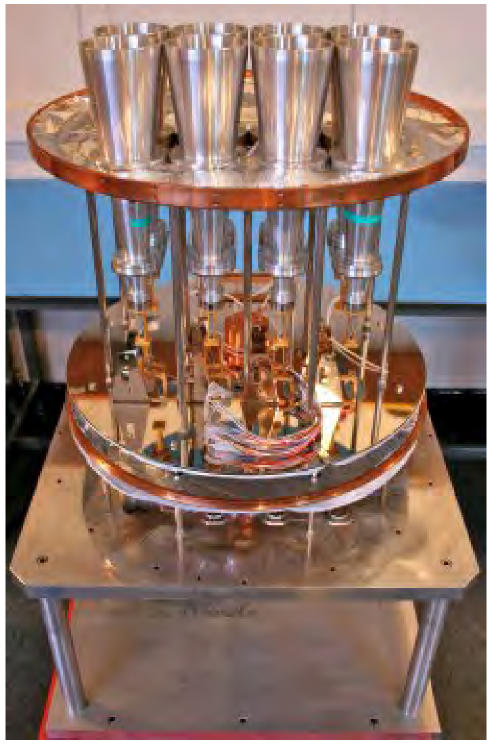

Figure 6.8: The One Centimetre Receiver Array – FARADAY (OCRA-F) has 8 beams, with the space for expansion to 16 beams. The receiver uses MMICs in place of traditional components. OCRA-F will be used to do small-scale blind surveys for point sources and the Sunyaev-Zel'dovich effect, and will also be able to create maps of extended emission. The project aims to construct a one-hundred beam receiver system, operating in a frequency band centred on 30 GHz (Browne et al., 2000).

Tens of receiver elements

When many tens of receiver elements are required, it is appropriate to begin integrating sub-assemblies into multi-chip modules. Usually these modules will be assembled manually by skilled technicians. It is expected that the MMIC chips themselves have a fairly high yield or are otherwise screened for performance on-wafer before being assembled into these modules. Improvements in MMIC technology over the past decade and particularly the availability of a wide variety of catalog MMIC chips from several vendors up to at least the lower-part of the millimeter-wave range have made this an extremely viable solution for many projects. Although size-reduction is moderately important, it is usually not worth deviating from standard connectors or waveguide flange dimensions.

Examples of arrays that fall into this category include the Five College Radio Astronomy Observatory's SEQUOIA instrument, the OCRA-F prototype array at the University of Manchester (Fig. 6.8), and to a lesser extent, parts of the EVLA Ka- and Q-Band receivers as well as the ALMA Warm Cartridge Assemblies. It is worth noting that a degradation in module performance as compared to MMIC chip performance has been noticed in a number of existing arrays. This can be due in part to a non-optimized packaging arrangement, which should be addressed.

Although the techniques for this approach have reached a respectable level of maturity, some improvements are still possible and may facilitate its more wide-spread use in arrays of this size, as well as in sophisticated space-based receivers where size and weight are at a premium.

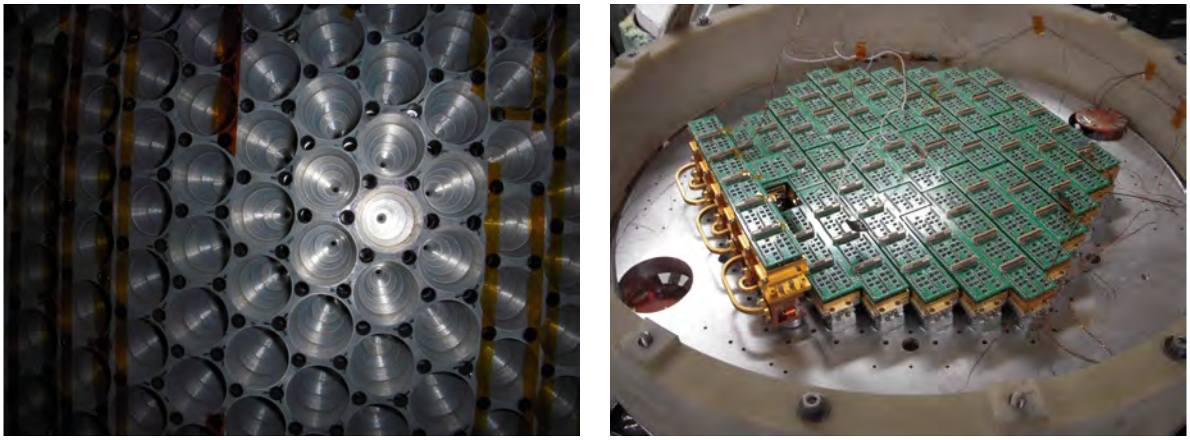

Figure 6.9: 91-element 90-GHz (W-band) array for the QUIET experiment. *Left:* View of the platelet array of corrugated horns. *Right:* Compact OMTs and MMIC polarimeters are attached on the underside of the platelet array. QUIET is making very sensitive measurements of the polarization of the cosmic microwave background radiation, using the technology of coherent correlation polarimeters. The arrays consist of receivers at two frequencies (40 and 90 GHz) and are deployed on a telescope at 5 080 m in the Chilean Andes.

Hundreds of receiver elements

Once an array grows to more than about a hundred receiver elements, it is no longer practical to assemble modules manually. Instead, it is preferable to design the module to allow for automatic assembly by pick-and-place machines and possibly automatic wire-bonders. Size and weight are also critical design parameters, even in ground-based applications. Innovative interconnect solutions and custom flange arrangements are often justified, and specialized test fixtures will need to be built in order to characterize modules coming off the assembly line efficiently. Insufficient yield and process stability can easily become the dominant factors in production schedule and cost. As a general rule, it is preferable to discard modules that do not meet specifications than to spend time troubleshooting them, and this should be built in to the production schedule, with a budget based on the best predictions of the expected yield.

A good example of an instrument of this size is QUIET (Fig. 6.9).

As many future instruments will fall into this category, it is an area in which the Keck Institute can have a significant impact. There is plenty of room for improvement in the areas of signal distribution, integration of electromagnetic components (i.e., feeds and OMTs), automated assembly, and smart module layouts that allow for a compromise between compactness and *in situ* testability.

Thousands of receiver elements

With the exception of a few large bolometer cameras and some very low-frequency arrays, no radio astronomy instrument consisting of a thousand or more receivers has yet been built. There have on the other hand been a small number of non-radio-astronomy receivers made at this scale, such as the Passive Millimeter-Wave Imager constructed in part by Northrop Grumman Corporation, and, while they are not subject to the same constraints and requirements as would be needed for radio astronomy, there is still much that can be learned from these projects.

Present thinking is that constructing an array of this size will require integration of multiple-functions, if not the entire analog receiver, on a single chip, or in a 3-dimensional multi-technology chip-stack. The latter is sometimes referred to as Wafer-Level Packaging, and involves bonding together wafers from different mask sets and even different technologies that are then diced into bricks, creating a multi-layer "chip."

Table 6.1: Preferred Packaging Solutions

# of receivers	Preferred packaging solution	Comments
1–9	assembly of individually connectorized components	yield not critical, design for greatest ease of test and troubleshooting
10–99	sub-assemblies of manually assembled multi-chip modules	use standard connectors and flanges for ease of testing
100–999	sub-assemblies of automatically assembled multi-chip modules	use custom flanges and connectors for reduced size and weight
1 000–9 999	integrated multi-function chips, wafer-level multi-chip packaging	yield is very important, testing on pass/fail basis
10 000+	full-wafer receiver sub-arrays	yield is paramount, any failures will result in dead beams

This process is extremely new and would require some further development and testing before it can be used readily in science applications. First and foremost, the process must be qualified for cryogenic operation, as there may be an issue with the coefficient of thermal expansion mismatch between the layers that can cause them to fail when cooled. Reliable handling and mounting techniques will also have to be developed, as well as a general body of experience among radio astronomy engineers, with the design of circuits that are compatible with this process and the idiosyncrasies that it may entail.

At this scale, it becomes advantageous to automate testing and characterization of receiver elements. Modern assembly techniques allow the construction of components to outpace the testing. This is particularly true where cryogenic testing is involved. Techniques must therefore be developed which allow for cold testing of 20 or more parts, on timescales of 1 day. Careful consideration must be given to cryostat times, and component interfaces to allow for test integration in a very short turnaround time. Furthermore, testing of elements for an array of this size has to be done on a pass/fail basis. There will not in general be time to diagnose and fix problems that may occur with individual receivers, they will simply have to be discarded. Clearly, this in turn requires the process technology to be mature and have a fairly good yield.

Tens of thousands of receiver elements

The realization of ultra-large-format heterodyne imaging cameras with 10 000+ receiver elements will depend on the very highest level of integration and automated processing. We believe that this can only be achieved if entire receiver arrays can be made in whole wafers, un-diced, possibly in a multi-wafer stack as described above, with a minimum of external connections for antennas and outputs. There will be no mechanism available for repairing or replacing receiver elements that do not meet specs. Obviously this will require wafer-scale technologies with extremely good yield.

The feasibility of this approach is entirely speculative at this point. In addition to all the same issues associated with wafer-level packaging above, significant thought must be given to developing an efficient means of coupling energy into and out of the wafer stack. Superconducting, microstrip-fed, phased-array antennas provide one possible solution to the problem, at least on the input side. Ideally, outputs would either be direct-detected voltages on copper traces, or grouped into a fiber bundle connected to the bottom of the stack carrying baseband signals ready to be digitized, or pre-digitized signals ready for signal processing.

Summary

These preferred solutions are summarized in Table 6.1. Of course, the size thresholds given there are only approximate and the specific process stability and yield of the technologies used as well as the required performance for a given application may tend to bias the preferred packaging solutions to slightly higher or lower numbers. However, it is also fair to say that extreme cases of process variability or low yield will rule out some of these solutions entirely, and consequently make arrays of a certain size totally infeasible. Maturation of these technologies, both at the device level and the packaging level, is therefore essential if focal plane arrays containing thousands or tens of thousands of receiver elements are ever to be realized.

6.3 Instrument level

6.3.1 Signal distribution

Large arrays of receivers have to overcome problems associated with signal distribution. These signals range from the mundane—such as bias controls and detector diode signals—to the more difficult problems of LO and IF distribution.

The LO distribution problem has plagued previous array spectrometers. In the past the LO was distributed either by waveguide or coaxial transmission lines. This is extremely convenient for module testing, but rather inconvenient for integration of large arrays. New techniques exist for LO generation and signal distribution, ranging from efficient oscillators at the receiver to low power, low frequency oscillators backed by multipliers and amplifiers. Careful study is required to find an appropriate and optimal distribution scheme. A great deal of work has been performed by the telecommunications industry, aimed at low cost distribution of millimeter wave signals, based upon surface mount components and printed circuit boards.

When considering broadband spectrometers, IF signal distribution also becomes a problem. IF signals with 20 GHz bandwidth require special attention. To minimize crosstalk, issues such as placement of IF gain blocks require careful attention. Again we need to look to the commercial sector for cost-effective broadband solutions. Mass termination connectors and cables exist with more than 10 GHz bandwidth.

6.3.2 Feeds

Several approaches to mass-producible, high performance feed arrays are being pursued. One of the most promising is a new type of horn that is much lighter and much easier to fabricate than corrugated horns. It is a smooth-walled conical horn with 3–5 flare discontinuities, as shown in Fig. 6.10. The idea of operation is based on the Potter horn design but with additional discontinuities that allow the controlled excitation of higher-order modes along the horn. Accurate choice of the location and magnitude of these discontinuities allows substantial broadening of the bandwidth and a much simpler and faster fabrication procedure compared to the traditional corrugated horn (Yassin et al., 2007).

Design method The design of these horns is based on the combination of a synthesis and analysis software packages. The analysis package is modal matching software that computes the radiation pattern of a horn with a given geometry. The synthesis package is a genetic algorithm search routine that selects a sub-group of horns for analysis according to "fitness" criteria and required bandwidth. The genetic algorithm yields a subset of the horn population in which the global optimum which is located using down-hill simplex optimization (Kittara et al., 2007).

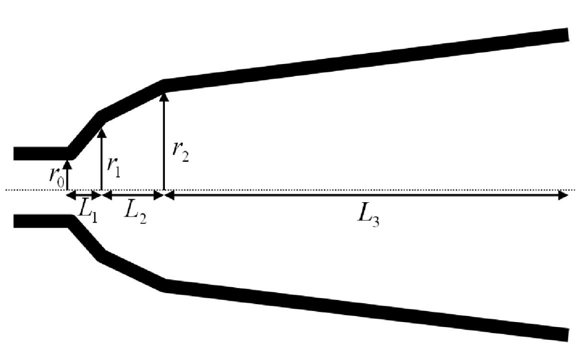

Figure 6.10: Cross-section of smooth-walled conical horn.

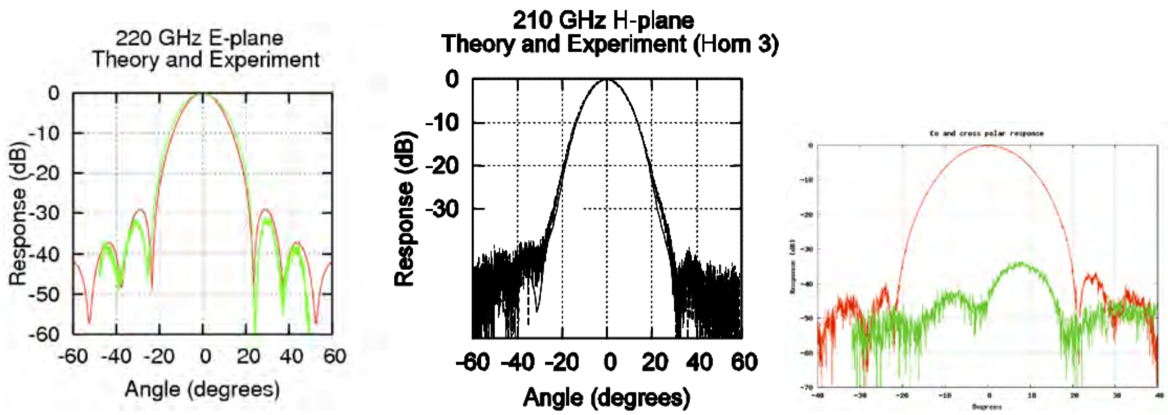

Figure 6.11: Radiation pattern of multiflare smooth-walled horns centred at 220 GHz.To test the integrity of the design method a 3-step electroformed horn has been fabricated. The experimental results show excellent agreement between theory and experiment. The cross polarization of the horn is comparable with what can be obtained from corrugated horns. (a) Comparison of theory and measurement of radiation pattern of electroformed horn. (b) Measured cross polarization. (c) Radiation pattern of drilled horn.

Method of fabrication An attractive feature of these horns is that they can be fabricated very quickly and very cheaply. One way of doing it is to fabricate a "drill bit" so that the horns arrays can be milled directly into a block of aluminum. This drilling method not only allows quick fabrication of individual horns, but also facilitates the manufacture of integrated 2-D arrays of horns quickly and economically. High performance milling machines are capable of maintaining $\pm(2\text{–}3)$ μm tolerance between the waveguide and horn, maintaining the expected horn performance even at high frequencies. At the Steward Observatory Radio Astronomy Lab, drilled feedhorns of this type are being fabricated at frequencies up to 1.3 THz. The technology has been used to fabricate several horns at 220 GHz. The excellent agreement between theory and experiment (Fig. 6.11) demonstrates that fabrication of horns in this method is feasible and that the predicted tolerences (more than 20μm at 220 GHz) are easily achievable.

6.3.3 Orthomode transducers

An orthomode transducer (OMT) is used to extract two orthogonal polarization modes from a rectangular or circular waveguide. The most stringent performance requirements on OMTs for arrays are required by the CMB B-mode experiments. These instruments require an OMT with extremely low cross-polarization

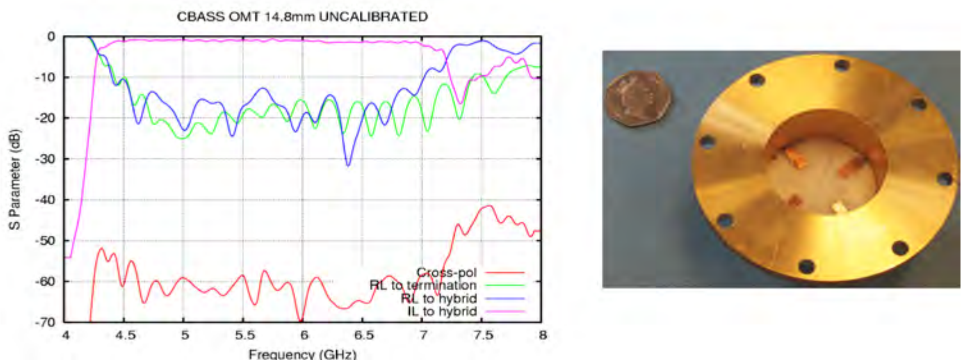

Figure 6.12: *Right:* The 4-probe OMT at 5 GHz. *Left:* Measured insertion loss (upper trace), return loss (green trace), and isolation (lower trace). The OMT has broad-band performance and excellent isolation. Note that the component is used both for coupling of power from the waveguide to the detectors and as an OMT.

(of order −50 dB or less) and near-equal insertion loss of the two orthogonal modes over a relatively wide band. Dual polarized arrays for other applications also require OMTs, but with somewhat more relaxed performance requirements. For array applications, the OMT must also be compact, easy to fabricate and integrate with detectors and amplifiers, and coolable to cryogenic temperatures.

Various waveguide OMT designs are well known (Wollack et al., 2002; Skinner & James, 1991), but these tend to be bulky, and are difficult and expensive to fabricate for high frequencies. These devices are also intrinsically three dimensional, making them very difficult to integrate into large 2-D focal plane arrays. The development of these components for array applications is focussed on manufacturability, both by electroforming and direct machining in split blocks.

Hybrid waveguide/planar circuit designs have also been considered at mm-wave frequencies—e.g., finline OMT (Chattopadhyay & Carlstrom, 1999), turnstile junction with planar circuit combiners—with somewhat simpler fabrication requirements.

Fig. 6.12 shows a four-probe planar OMT, which consists of four waveguide probes arranged 90° apart around a cylindrical waveguide and extracts the two orthogonal polarizations by combining the signals from each pair of opposite probes (Grimes et al., 2007). This OMT is extremely compact and easy to fabricate, requiring only machining of a circular waveguide backshort, and it allows the waveguide probes to be integrated with the detector/MMIC substrate. This design has been shown to be capable of meeting all of the performance requirements for CMB B-mode and foreground experiments in the cm-wave band and it is now being developed for array applications in the high mm-wave band. The major technical developments required to allow the use of this OMT in array applications are in the area of integrating the waveguide probes with detector/MMIC circuits and substrates.

While this OMT design does require four frontend amplifiers rather than two, along with two IF chains per polarization, they are entirely compatible with I-Q downconversion schemes. When used as a component in a large focal plane array (either MMIC or SIS), I-Q downconversion will most likely be used to increase the IF bandwidth of the receiver system. The 4-probe OMT, when used in this configuration, reduces the overall complexity of the frontend system.

6.4 Digital correlators and spectrometers

Progress in digital signal processing technology has been driven at a rapid rate by funding for telecommunications, games, and other commercial electronics applications. Commercially available high performance analog-to-digital converters (ADCs), field programmable gate arrays (FPGAs), application specific integrated circuits (ASICs), and wide bandwidth network switches make possible construction of correlators and digital spectrometers with an unprecedented combination of high performance and low cost. The low cost of FPGA chips and the design flexibility that they offer result in low start-up costs and easy reconfigurability. ASICs offer significantly higher performance and lower power consumption, but higher up-front costs for design and fabrication. Where mass and power consumption are of paramount importance (i.e., space or extremely large ground-based correlators), the up-front investment in ASIC development and production is extremely cost effective. In the last couple of years, ASIC technology has crossed an important threshold: *large correlators in space, and large, low-power correlators on the ground, are now possible.* While this point is not yet widely known outside of the space-based correlator community, it has been a key development for several of the breakthrough instruments described in Chapter 4.

We describe below the current state of FPGA and ASIC technology.

6.4.1 FPGA correlators and spectrometers

A correlator system comprises band-selection downconverters, ADCs, antenna-based digital processing (delay tracking, beam-forming), and correlation logic. The processing limits of one system impact the design of the other systems; they cannot be treated in isolation.

Current ADCs operate at sample rates up to 2 Gsps in deployed systems and 6 Gsps in prototype systems, and up to 8 bits per sample. Depending on the application, all bits from the ADC can be taken onto an FPGA, or some can be discarded. For example, two bits might be used for lag-based systems, four bits for Fourier transfer, or more bits used in digital filtering applications.

Samplers can be interlaced to obtain higher effective sample rates, up to a total input analog bandwidth of about 2.5 GHz. For example, current FPGA technology operates with clock frequencies in the range 125–400 MHz. (Higher frequencies are achieved at the cost of higher heat dissipation.) A 1 GHz sampler can be constructed by multiplexing eight samplers running at 125 MHz.

The correlators for the SZA (8 antennas, 28 baselines) and CARMA (15 antennas, 105 baselines) interferometers are wide-bandwidth systems (8 GHz and 4 GHz, respectively) that use a hybrid combination of analog and digital electronics. FPGAs generate 100 channels across 500 MHz and up to 1 K channels over narrower filtered bands (62.5 MHz and lower). The limit to the number of channels is imposed in part by the physical size of the system. Analog downconverters are used to filter 500 MHz wide bands from the 4 GHz wide IF, and downconvert those signals to 500–1000 MHz. The 500 MHz-wide bands are then sampled at 1 Gsps.

There are two points to note from this type of design. First, wide bandwidths require a lot of analog downconversion hardware, and the cost of the analog hardware can become a significant fraction of the correlator system cost. Second, the ADC sample rate, analog filter bandwidth, and downconverter output bands are intimately related. If the sample rate of the ADC used in the system is, say, doubled to 2 GHz, then the downconverters would require redesign to generate a 1 GHz wide output band, and that band would most likely be placed between 1 GHz and 2 GHz (this simplifies the analog electronics design).

The Berkeley Wireless Research Center is collaborating with numerous correlator development groups to help speed up system development.[3] The objective of the MeerKAT prototype system is 16 K-channels, 500 MHz bandwidth, for 30 to 80 telescopes. This system is not complete, but it is a good example of the state of the art.

For the near future, Agilent has 20 Gsps sampler technology that they are willing to make available for use in correlator development. Integrating a 20 Gsps sampler within a digital system will be a non-trivial task. Clock jitter in the ADC clock source and I/O rates on the FPGAs will be design challenges. However, we believe that a 20 Gsps sampler operated at 12 Gsps can be interfaced to current-generation FPGA technology. A 12 Gsps sampler and digital filtering logic has the potential to replace eight bands of

[3] `http://casper.berkeley.edu/wiki/index.php?title=International_Correlator_Collaboration`

analog downconverter hardware. For other spectrometer and correlation applications, there are undoubtedly many applications that would benefit from these samplers. Wider bandwidth systems can still use a hybrid approach where the input signal is filtered into 5 or 6 GHz wide bands, but compared to a system with 1 Gsps samplers, there would be an order of magnitude fewer bands.

The integration of a 20 Gsps sampler (operated at 12 Gsps) will be the focus of active research over the next couple of years. Research after that point can then determine if 40 Gsps or 80 Gsps samplers should be used, or whether wideband sample-and-hold circuits that can be used directly to digitize signals in the IF up to 100 GHz would be a more useful technology to pursue.

System-level issues in two particular correlator cases deserve mention. The first is that of large format focal-plane array receivers on antennas, which results in a linear increase in the correlator requirement. The effect on the size of the correlator itself is easy to comprehend. What is not clear, is how one would get many wideband signals from the focal plane of the antenna to the correlator. In radio interferometers, 180° phase-switching is used to reject common-mode signals between antennas. Common mode coupling would be worse on cables from the same antenna. Orthogonal Walsh functions are used for the phase-switch sequences. If Walsh switching was used on a focal plane array with a large number of elements, then the Walsh sequences across the array would have to be long, and hence either the period of a phase-switch would have to be very short, or the integration times very long.

The second is that of beamforming with phased-array feeds. Since the beamformer electronics are antenna based, they could be placed close to the focal plane on the antenna. However, a key issue to investigate is what kind of RFI does the correlator system produce, and what kind of RFI tolerance does the system have. If the system is using 10 GHz or 20 GHz ADCs, harmonics of the sampler are bound to lie within the IF of the receiver.

6.4.2 ASIC correlators and spectrometers

Recent technology developments with space-based cross-correlators for Fourier synthesis interferometers have been driven by several proposed Earth Science remote sensing missions, in particular the Lightweight Rainfall Radiometer (LRR) and the Geosynchronous Earth Orbit Synthetic Thinned Aperture Radiometer (GEOSTAR). In both cases, emphasis has been placed on reducing power, increasing clock speed, and improving the radiation tolerance of the digitizers and the multipliers/accumulators. Ultra-low power CMOS ASICs are used, based on a 0.5 V logic protocol with resistance by design to radiation-induced single events. This protocol has extensive spaceflight heritage for other high-speed digital signal processing applications in space.

Two-bit digitizer ASICs fabricated in $\sim$2002 for the LRR program required 5.5 mW while sampling at $\sim$220 MHz. At the maximum sample rate of 300 MHz, the DC power draw rose to 9.5 mW. A 0.5 V CMOS 2-bit 25-channel complex multiplier/accumulator ASIC was also developed for LRR at this time. It included a front-end digital quadrature demodulation stage to form the In-Phase and Quadrature-Phase components of the input signal, followed by complex multipliers and accumulators for all possible pairs of the 25 complex signals. When clocked at $\sim$220 MHz, the chip drew 1.5 W. Both ASICs were built using 250 nm design rules.

Since 2002, other non-correlator digital signal processing projects have pushed the ultra-low power 0.5 V CMOS process from 250 nm to 90 nm, allowing significant improvement over the earlier LRR ASIC performance. A development effort began in July 2008 to create a new multiplier/accumulator ASIC for the GEOSTAR project using the 90 nm geometry. It is projected to be capable of complex cross-correlations of all possible pairs of 196 In-Phase and 196 Quadrature-Phase 2-bit input signals, clocked at 1400 MHz, while drawing 1.68 W of DC power.

With the currently available technology, **large correlators in space are possible**. This point is currently not widely known outside the space-based correlator community.

Further reduction in the power dissipated by 0.5 V CMOS ASICs and further increases in their maximum clock rates will be possible as the designs decrease further in size. Preliminary developments are underway at 65 nm for other applications outside Earth science and are expected to continue. These developments should eventually mature to the point where they can be used for space science applications. An acceleration in that development process would require additional infusion of funds. In particular, the development of faster and lower power digitizers has lagged behind that for the multiplier/accumulator chips. In order to maintain a reasonably close match between the maximum clock rate capabilities of the digitizers and multipliers/accumulators, additional development funds will be required for the digitizers. The first step would be development of 90 nm versions of the LRR-style digitizers. Based on the modeling projections made for the 90 nm multiplier/accumulator ASICs, this can be expected to result in digitizers with maximum clock rates in the neighborhood of 1400 MHz. Current flight-qualified digitizers capable of $\sim$2 GHz clock rates require $\sim$2 W of power to operate. The power needed is much too high to be supportable for typical large-N interferometer systems. A 90 nm ultra-low power 0.5 CMOS ASIC digitizer can be expected to dissipate about two orders of magnitude less power than the LRR digitizers.

6.4.3 Summary

The key chip technologies central to correlators and digital spectrometer backends—FPGAs and ASICs—are advancing rapidly, driven by commercial demands. FPGAs have the advantage in design flexibility and low initial cost; ASICS have the advantage in performance and low power. ASICS have crossed an important threshold: it is now possible to build a big correlator (thousands or tens of thousands of baselines) for deployment *in space*. Instruments previously impossible to fly are now possible. Although the basic technologies are driven effectively by commercial interests, specialization to the scientific requirements of correlators or spectrometers still requires some development funding.

7

Roadmap for Development

The workshop achieved a strong consensus on a number of goals that must be achieved to realize the full promise of coherent instruments for CMB polarization in space. We list them in rough priority order (rough because there is not a single axis for prioritization, and the goals are not all strictly independent), with the first two the most fundamental and the most general.

1. Reduce the noise levels of individual transistors and MMICs to three times the quantum limit or lower at cryogenic temperatures at frequencies up to 150 GHz.
2. Integrate high-performing MMICs into the building blocks of large arrays without loss of performance. Currently factors of two in both noise and bandwidth are lost at this step.
3. Develop high performance, low mass, inexpensive feed arrays.
4. Develop robust interconnects and wiring that allow easy fabrication and integration of large arrays.
5. Develop mass production techniques suitable for arrays of differing sizes.
6. Reduce mass and power. (Requirements will differ widely with application. In the realm of planetary instruments, this is often the most important single requirement.)
7. Develop planar orthomode transducers with low crosstalk and broad bandwidth.
8. Develop high power and high efficiency MMIC amplifiers for LO chains, etc.

Below we describe each of these goals in turn, and then consider the path from technology development to full-up instruments.

7.1 Goal #1: Improve device noise performance

Our goal is to reduce the equivalent noise temperature achievable with cryogenically-cooled InP HEMT transistors by a factor of 2–3 from current limits, to less than three times the quantum noise. Based on measurements of existing 35 nm gate MMICs at room temperature above 160 GHz, this should be achievable within the next two years in the frequency range 30 to 120 or 150 GHz, and up to 300 GHz on a longer timescale. To this end, we will:

- Measure and study existing devices and circuits for cryogenic performance and behavior to improve device physics understanding, and to guide and focus future device development.

- Develop new devices for multiple iterations of fabrication runs. Measurement and analysis after each run will inform the next.
- Optimize devices and circuits for cryogenic performance. Although the noise of existing devices is an order of magnitude lower at cryogenic temperatures than at room temperature, no serious attempt has been made so far to optimize HEMTs for cryogenic operation.

7.1.1 Work, participants, and location of work

This work is well-suited to a combination of university labs, JPL, NRAO, and NGC, with characterization and testing of devices both at ambient and cryogenic temperatures performed by postdocs and graduate students supervised by experienced senior researchers, and detailed materials modeling, device design work, and fabrication performed at NGC. Cryogenic testing and characterization and testing of devices is the core of this effort, and will be centered in the new Cahill Radio Astronomy Laboratory (CRAL) in the Cahill Astrophysics building on the Caltech campus.[1] This work is especially appropriate for postdocs and graduate students because it requires ability and physical insight, rather than great experience, and it is aimed at a fundamental understanding of the devices as well as fabrication of the devices themselves. Research papers and several astrophysics PhD theses will be the ultimate products of successful work. Additional measurement capability will exist at JPL, NRAO, the University of Massachusetts, and Stanford University. All of these institutions will be involved in modeling of devices, guided by extensive measurements. In addition, the University of Manchester (supported by external funds) will undertake investigations of devices specifically aimed at improving cryogenic performance. We will also work with the Fraunhofer Institute for Integrated Circuits in Erlangen, Germany, on the fabrication of new devices.

Wafer probing at cryogenic temperatures is required to characterize devices and circuits, enabling critical feedback into the device and manufacturing process. We have built a cryogenic probe station to meet the unique requirements of these low noise, high frequency measurements.

A specialized test structure is needed to extract specific information critical to the physical understanding and device optimization goals of the program. It will take the form of a millimeter-wave gain block, using ungrounded coplanar waveguide transmission lines so that it can be probed prior to wafer thinning and provide immediate feedback to the foundry. It will be broadband, about 40 GHz wide in W-Band (75–110 GHz), have 15–20 dB of gain, and be unconditionally stable. Short-open-load-thru (SOLT) calibration structures will be integrated into the test structure itself, along with a transistor gate diode for *in situ* temperature monitoring, to facilitate extraction of the device data.

The core equipment in the CRAL is a cryogenic wafer probe station, along with the necessary peripheral equipment, including a millimeterwave capable vector network analyzer, spectrum analyzer, and power supplies, with the following capabilities:

- Probe existing MMICs
- Perform automated testing on reticules across the entire wafer
- Perform calibrated, cryogenic, two-port S-parameter measurements from DC to 110 GHz
- Hold wafers in place, cool them, and remove them without damage
- Measure equivalent noise temperature
- Automated extraction of DC I-V curves, including secondary terms such as gate leakage.
- Integrated test heads to allow low-loss measurements at the device plane (desired, not required)
- Cooling to 20 K within 2 hr.
- Ultimate cooling temperature of 4 K (desired, not required)

[1] The CRAL is directed by Professor Tony Readhead and Faculty Associate Todd Gaier, managed by Senior Research Fellow Kieran Cleary, and staffed by Keck Institute Prize Fellow Oliver King, postdoc Rodrigo Reeves, graduate students, and a technician.

7.1.2 Issues that must be addressed

Performance improvements will require addressing or solving the following issues, which are thought to limit performance currently.

Shot noise due to excessive gate leakage In pursuit of the highest gain and transconductance InP HEMT devices, excessive leakage current at operating conditions limits the ultimate noise performance, especially at low frequencies where thermal noise is low. Current research into alternate gate metals, barrier designs, gate recess chemistries and etch stops may improve both the turn-on voltage and reverse gate leakage for the InP HEMT devices while maintaining the other key DC and RF parameters. Of greatest interest is reduction of gate leakage at cryogenic operation, which has not been studied or optimized carefully. NGC and JPL have observed wafer to wafer and lot to lot variation in the gate leakage. Future improvements in device performance at higher frequencies will necessitate low gate leakage below 1 μA to realize the next levels of noise performance.

High ohmic resistance at cryogenic temperatures Recent investigations have shown that InP HEMT ohmic contacts are not optimal and studies of the ohmic contact resistance to cryogenic temperatures may be important. This will have an impact not only on device gain, but also on the optimal DC bias voltage/current needed to achieve usable gain and its effect on drain temperature. Alternate ohmic contact and epitaxial schemes look promising for $> 2\times$ improvement, which may translate directly to cryogenic device noise improvements. Limits of epitaxial doping and design have also not been explored, especially for cryogenic operation.

Anomalous cryogenic HEMT behavior Although not consistently observed, known potential issues such as IV kink at cryogenic temperatures (light sensitive), high output conductance, poor device pinch-off, low breakdown devices, high leakage and gain fluctuation need to be understood and avoided. Customized cryogenic tests can be developed to study these problems and learn how to avoid them. In some areas, promising room temperature solutions have been developed, and it will be beneficial to translate these improvements to cryogenic products.

InP HEMT yield limiters Ohmic contact and sheet resistance, gate yield and defects, device breakdown, gate leakage, damaged airbridges, via hole yield, back metal adhesion, TFR damage, probe and metal scratch damage, dicing (splitting die), wafer breakage, and line errors are all factors.

Cryogenic device and noise models Pospiesalski's cryogenic model is simple and predicts the noise parameters and overall performance of low noise amplifiers fairly well, especially for discrete device amplifiers. Improved cryogenic HEMT noise models are important to ensure that future designs achieve the best possible noise performance.

Over the past several years, NGC has pioneered the use of advanced semiconductor materials, epitaxial designs, ohmic, gate and interconnect metals, device topologies, passivation thickness and interfaces, and backside wafer process improvements for its HEMT devices. The central focus for these advances at NGC continues to be to improve room temperature noise figure performance of LNAs, with low DC power consumption and further system advantages in size and weight that can be derived through higher frequency implementations. These products are primarily aimed towards insertion into NGC's satellite communication payloads. To spur these innovations, NGC has invested significant internal R&D funding for device and MMIC research (totaling more than \$10 M/year) and has consistently won contract R&D funding mainly from DoD services (also totaling more than \$10 M/year) over various semiconductor devices and products. NGC also continues to invest a large amount of semiconductor equipment capital (also easily exceeding \$10 M/year) especially to develop these novel materials and devices.

What has not been studied recently is how these advances may spur improvements in the cryogenic operation of these devices. It can be projected that the room temperature improvements, especially in noise performance, may translate to improvements with cryogenic operation, but a careful engineering study and optimization have not yet been conducted. Key innovations—both near and long term—that can improve the state-of-art for cryogenic noise performance include the following:

Nanometer-scale gate length reduction Short gates (70 nm and 35 nm), in combination with optimized epitaxial profile designs, have demonstrated reasonable yield and reproducibility. The use of these device technologies has focused mainly on a new generation of amplifiers from 140 GHz to 400 GHz, but extremely high device gain may also provide distinct low noise advantages at any frequency where the device and amplifier noise performance is gain limited.

Atomic-scale material growth and design Advanced HEMT materials may offer higher frequency operation and low noise performance. Electron transport in InGaAs channels grown pseudomorphically on InP substrates has been improved with InAs channels (100% indium) through the design of a composite channel epitaxy design. Extremely high room-temperature mobilities of 16,000 $cm^2\,V^{-1}\,s^{-1}$ have been observed, which represents a 30–50% increase compared to the baseline 60% InGaAs channels. Further study of these devices is necessary to determine whether alloy scattering and impact ionization dominate in cryogenic operation. ABCS (antimonide-based compound semiconductor) devices employing metamorphically grown InAs and potential InAsSb channels represent future material innovations that could push mobilities and electron velocities to even higher values. The limited cryogenic tests made so far have not yet demonstrated new state-of-the-art performance, and current challenges in material quality, high leakage, and impact ionization still need to be addressed.

Device parasitics Significant improvements have been made recently in ohmic contact and access resistance, in both epitaxial designs and new refractory ohmic metals. Contact resistance improvement by as much as 3× and sheet resistance improvement of 50% have been achieved on the most successful devices at room temperature, and should benefit cryogenic operation and low noise performance. Further development and exploration of sheet resistance limits through new epitaxial designs and smaller ohmic-to-gate spacings, including self-aligned gate device schemes, should be part of further work. Reduction of resistance in cryogenic operation is critical for lowering operating drain currents and voltages for high gain, which ultimately reduces drain temperature in the standard cryogenic FET model. Innovations for reduction of capacitance parasitics with both alternate low-dielectric-constant passivation films and thinner passivation films should be explored. Thinner passivation has been employed on recent high frequency devices and should be studied for potential benefits with cryogenic operation.

HEMT gate innovations For HEMT devices, the gate process and the metal-semiconductor junction remain the most critical in determining device performance. Barrier height and threshold voltage are crucial in optimizing device transconductance and gain, but breakdown and leakage current must be controlled to achieve a useable device. Often these requirements conflict, and the trade-offs are even less understood at cryogenic temperatures, where certain leakage currents are suppressed while others are enhanced. The gate recess process formation is equally critical as it impacts breakdown, leakage, and access resistance. Many of the effects and variations with cryogenic operation have not been carefully studied and optimized. Several innovations are being explored. New refractory gate metals, especially Mo and TiW, may provide lower leakage and superior cryogenic Schottky junctions. Controlled interdiffused junctions that could reduce $1/f$ noise for cryogenic operation have not yet been explored. Epitaxial growth is still critical, and although not studied to date, heterostructure and doping interface sharpness may be critical to determine limits on gate-to-channel separation, where we face trade-offs between transconductance and gain vs. excess leakage and degraded Schottky junctions. These trade-offs, along with new refractory metals, should be explored for optimal cryogenic performance. Tailoring the gate recess profile through etch stops and multiple recess steps may provide advantages where the designs are aimed towards cryogenic low noise operation. However, current research is aimed more towards higher power, higher device-density circuits. Barrier-layer epitaxial designs for both etch stop and bandgap engineering should be studied more carefully for cryogenic optimization. As an example, current ABCS HEMT device use is limited owing to problems manufacturing the gate barrier layer of AlSb and GaSb.

New devices, materials, ideas New transistors and materials, when they come to some level of maturity and utility, may be crucial to achieving noise of $3q$ or better. Among the promising technologies being pursued are quantum wire devices, as well as carbon nanotube and graphene transistors. Nanolithography will also push the limits on device scaling and we anticipate research using gate-lengths of 20 nm or less, with the goal of achieving amplifiers that could operate as high as 1 THz. Optimizing these new concepts for cryogenic noise operation may also reveal further, unexpected performance breakthroughs.

7.2 Goal #2: Integrate MMICs into arrays without loss of performance

The overall goal of the work is to achieve near-quantum-limited performance in the basic building blocks of massive arrays of coherent detectors for radiometry, polarimetry, interferometry, and high resolution spectroscopy in the frequency range 70–280 GHz. The key now is to realize the full performance potential of the transistors and MMICs (as developed in Goal #1) in a unit cell package that enables massive arrays. This requires cryogenic measurement and characterization of MMICs and other components, isolation of the critical factors in performance, design and fabrication iterations, and exquisite control of fabrication. Specific goals are to produce modules (both direct detection for continuum work and heterodyne for spectroscopy and interferometry) with the following noise performance:

1. $< 3q$, 70–118 GHz (current state of the art is $6q$)
2. $< 5q$, 120–160 GHz (current state of the art is $10q$)
3. $< 10q$, 180–280 GHz (current state of the art is $20q$)

These bands were chosen to meet programmatic needs: CMB polarization and astrophysical spectroscopy for bands 1 and 2; Earth and planetary atmospheric chemistry/spectroscopy/sounding for bands 1 and 3.

With the first year of KISS R&TD funding at JPL we have: developed a simple mask set of transistor cells and simple test amplifiers (MMIC) which will become a test mask to be repeated on subsequent wafer runs as the InP fabrication recipe evolves; designed a modified amplifier housing for W-Band with a tighter fit, and designed a new DC bias board that accommodates four bias lines, allowing for more degrees of freedom when optimizing noise; designed and fabricated waveguide modules to test the E-plane probe transitions in WR10 and WR5, allowing us to accurately account for the front-end loss in our low noise amplifier modules; designed a waveguide module for WR4 waveguide (we are continuing work on an E-plane probe transition for this band); and measured room-temperature noise data obtained from a MMIC Array Spectrograph module using 70 nm HEMTs, before placement of 35 nm InP HEMTs, which resulted in $<$400 K noise.

One of the goals is to demonstrate a polarimetric receiver module with the same noise figure as a cascade of individual amplifier modules. Measurements from one polarimetric module give 38 K and 42 K in the two arms. A prior measurement of a single amplifier module gave 30 K noise. These measurements show promise towards achieving that goal, but they must be repeated and verified.

7.2.1 Participants and location of work

The lead for this work would be in the low-noise amplifier lab at JPL, led by Todd Gaier, where the first module-level integration designed for cryogenic operation in this frequency range was performed, with NRAO, Stanford University, and the University of Manchester all participating in various aspects of testing, characterization, and prototyping.

7.3 Goal #3: High performance, low mass, inexpensive feed arrays

The goal here is to reduce mass and cost while maintaining a very high level of performance, assesed by sidelobe levels, losses, and bandpass characteristics. This work will focus initially on smooth-walled alternatives to corrugated feeds that promise excellent performance with greatly improved manufacturability.

A different possibility will also be studied, that of using a phased array of near-planar antennas in the focal plane of a large telescope. This type of array collects all the energy in the focal plane, and it can be re-imaged to any needed size with fairly simple optics. Any aberrations can be corrected by changing the weights in a vector sum of the elements. An entire 1000-element array of near-planar antennas could be built in a 15 cm square, with the entire construction nearly planar. The main issues are computing power (for beam forming), interconnects (edge length/1000 gives 0.6 mm per IF wire), and thermal.

7.3.1 Participants and location of work

Oxford University: Ghassan Yassin

Arizona State/University of Arizona: Chris Groppi + expert micromachinists at both institutions + grad students and postdocs. Direct contribution is machining.

University of Massachusetts: Neal Erickson. Phased focal plane arrays.

7.4 Goal #4: Array interconnects

If cryogenic investigation determines that commercial metallization is not suitable, lower thermal conductivity metal (e.g., phosphor bronze) will be evaporated on commercial substrate for cryogenic applications. Commercial connectors exist for ribbon interconnects for DC applications. For RF applications, we will investigate custom RF connector designs in microstrip, coplanar waveguide, or stripline, first through full-wave EM and mechanical analysis, then with test fixtures to measure performance via vector network analyzer measurements, and finally measuring cryogenic performance and reliability in a test cryostat fixture.

7.4.1 Participants and location of work

Arizona State/University of Arizona/University of Virginia: Chris Groppi + Chris Walker + Arthur Lichtenberger. A proposal to the NSF Integrative, Hybrid, and Complex Systems program is pending to develop this technology for use in large format coherent focal planes at higher frequencies. Results will be coordinated and shared with the KISS program.

7.5 Goal #5: Mass production techniques

Fabrication of precision micromachined waveguide structures is a vital component for almost all MMIC circuits. Sophisticated CNC machining techniques have been little used in micromachining of waveguide blocks because small numbers in the past have not demanded the effort necessary to implement and refine mass production techniques. Future focal plane arrays with many hundreds of modules will benefit greatly from these techniques. High performance micromachining systems at Arizona State University and the University of Arizona already offer large work volumes, high-speed CNC controllers, and high capacity tool-changers. Automated touch probes and tool measurement systems are in place. These machines can complete all machining operations on a waveguide block (both waveguide features and other low-precision machining) in a single run. The capability exists for palletization for the manufacture of dozens of blocks in one machine setup, at frequencies above 300 GHz. With the addition of pallet changers and automated part feed, production rates of dozens per day could be achieved. We will develop machining techniques to produce waveguide modules using these palletization techniques, and will be able to supply other efforts within the KISS program with necessary waveguide blocks at a low cost.

7.5.1 Participants and location of work

Facilities already equipped for this work are available at the University of Arizona (Chris Walker) and Arizona State University (Chris Groppi). They will work with Caltech and JPL to produce waveguide blocks for the KISS program while developing mass production techniques.

7.6 Goal #6: Reduce mass and power

This is in some sense a background task, with the requirements for low mass and power always on the list of desirable characteristics for any design and design improvement work. Low mass is an explicit component of Goal #3 above, and an implicit result of Goal #2.

7.7 Goal #7: Planar high-performance OMTs

We have not yet formulated a plan for the development of high-performance orthomode transducers. Performance metrics include bandwidth, isolation, and mass. Several design possibilities are being considered in the context of suborbital CMB polarization experiments.

7.8 Goal #8: High power, high efficiency MMIC amplifiers for LOs, etc.

High power MMIC amplifiers have proven indispensible for local oscillator systems, in particular the ALMA array and the *Herschel* HIFI instrument. GaAs power amplifiers covering all of W-Band (70–110 GHz) have enabled HIFI, by providing for the first time stable, reliable, high power sources to drive chains of submillimeter-wave multipliers for local oscillators in terahertz receivers. Similarly, broadband GaAs amplifiers for ALMA provided a solution to the problem of creating reliable LO sources to drive SIS mixers in an interferometric array with phase noise comparable to that of Gunn oscillators, but without mechanical tuning. Since the *Herschel* power amplifier hardware was delivered, and the ALMA MMIC designs have been finalized, there has been little available funding for future LO source needs.

In addition to local oscillators, transmitters for radar applications (mainly Earth science) are also needed for future missions. MMIC power amplifiers could enable new instruments. In the case of radar, a phased array of W-band power amplifiers could replace a single extended interaction klystron (EIK), which has a disadvantage of being extremely massive and suffers from a single-point-failure possibility, where a phased array of MMICs is inherently a redundant system.

While funding in the radio astronomy and Earth science community has been limited and little new research into improving high power MMICs is now taking place, industry has been making rapid advances in new materials for high power MMICs at microwave and millimeter-wave frequencies. Gallium nitride offers vastly improved power density possible compared to the GaAs *Herschel*-era devices, with extremely high breakdown voltages and nearly 1 W of output power already demonstrated in industry. Government funded programs (i.e., DARPA) have typically helped to fund these advances.

A goal for this program is to explore these new technologies (beyond *Herschel* and ALMA) for MMIC power amplifiers. Many needs exist for arrays requiring high power at W-band or Ka-band (CCAT, Earth science radar, SOFIA, etc.) but funding to pay for wafer fabrication in these new technologies is severely limited. Project schedules usually preclude the option of developing new chip designs from scratch using new and unfamiliar MMIC processes, further underscoring the need to foster an ongoing chip development effort.

7.8.1 Participants and location of work

JPL, Stanford, NGC, depending on funding to be determined.

7.9 Medium and long term development

The goals and work described above concern technology development, the essential first step in the program, and cover the near term. The ultimate goal of developing breakthrough instruments will require multiple paths through funding agencies and selection processes. There is no general formula for success, no single description of a process. Instead, we give an example of how we might proceed in one area. Funding for the steps given below would not come from KISS.

7.9.1 Roadmap for array development for astrophysics

1. Definition of Key Projects and Array Requirements The development of focal plane arrays should be driven by the science requirements as defined by the key projects envisioned to be carried out. Each project should determine the angular resolution, spectral resolution, frequency coverage and sensitivity level required. This will result in a matrix of array requirements to be addressed by the technical experts and thus will define the following steps in the roadmap.

This phase should take between 6 and 12 months, although the following phase can start before this first phase is complete.

2. Identification of Key Technology Development Areas We anticipate that the results of Phase 1 will place specific technological demands (including those described in the first sections of this chapter) that will require significant research efforts. The array requirements cannot be met with "off the shelf" technology. Development of key technologies is essential for the construction of practical instruments. Some areas which likely will be addressed in this phase of the roadmap include:

- Lower-noise MMIC amplifiers.
- Mass production of low noise receivers having a high degree of uniformity and low cost.
- Packaging and interconnection technology for efficient and reliable systems incorporating large numbers of pixels.

- Cryogenics system engineering including optimization of large-area, low-loss vacuum windows.
- Evaluation of optimum location for digitizing the signal.
- Interface with developments in digital spectroscopic back-ends and data transmission.

3. Construction and Deployment of *Pathfinder Instruments* on 5 Year Time Scale By *pathfinder instrument* we mean an array receiver which demonstrates a number of the new technologies essential for major advances in the field, and which can produce significant scientific results. It may be limited in the number of pixels and frequency coverage, and could be deployed on a relatively small telescope. It is envisioned to provide critical system level experience for the following phases of the roadmap as well as data with real astronomical impact.

4. Design Study for "Second Generation" Instrument on 10 Year Time Scale We anticipate that this phase of the roadmap will start several years after the inception of this program. At this time, there should already have been significant technical progress, and the extension to a more ambitious array will thus be a reasonable step forward. The lessons learned from the *Pathfinder Instruments* will be incorporated along with additional technological research into areas that are deemed to need development even after the previous phases of the roadmap. The key projects will be updated and array requirements revised. This effort, which could take a few years, will define the design of the "Second Generation" instrument.

5. Construction of "Second Generation" Instrument The "Second Generation" instrument will be significantly more ambitious than the "Pathfinder," but, after the preceding steps, should be relatively low risk in terms of technology and cost.

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